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Selecção de Estratégias de Planeamento da Rede de Transporte

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Abstract

This work presents a study over the Electrical Transmission Network strategic planning subject.

The case-study is the latest Transmission Network planning exercise, carried out by the Portuguese TSO – REN.

A general review over the Transmission Planning Activity (scope, underlying criteria and procedures) was made so that a decision-aid methodology could be formulated for a concrete case.

An analysis of the latest PDIRT document, which states the outlined investments for the Portuguese Transmission Network over the 2009-2014 horizon, was made and through an integration of the information there presented, a multi-criteria strategic planning problem was formulated. Then, a decision-aid model for coping with the selection of the best/desired expansion alternatives, taking into account the decision maker preferences, was developed and tested.

Special thanks

This work is dedicated to my family, who always gave me everything in life.
It is also dedicated to my girlfriend Sara.

A word of appreciation must be addressed to Prof. Dr. Manuel Matos, by the special attention with which he guided me through this final stage of a long but rewarding journey.

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Abbreviations

List of abbreviations (in alphabetical order)

CDF	Critical Decision Factors
DL	Decree Law
DN	Distribution Network
DSS	Decision Support System
EE	Environmental Evaluation
ENTSO-E	European Network of Transmission System Operators for Electricity
ER	Environmental Report
ERSE	*Entidade Reguladora dos Serviços Energéticos* (Regulation Entity of the Energy Services)
EU	European Union
IDE	Integrated Development Environment
ISO	Independent System Operator
MIBEL	*Mercado Ibérico de Electricidade* (Iberian Electricity Market)
MSW	Municipal Solid Waste
NES	National Electric System
PDIRT	*Plano de Desenvolvimento e Investimento da Rede de Transporte* (Transmission Network Development and Investment Plan)
PIR	*Plano de Investimentos de Rede* (Network Investments Plan)
PNBEPH	*Plano Nacional de Barragens de Elevado Potencial Hídrico* (National Plan for Dams with High Hydric Potential)
REE	*Red Eléctrica de España*
REN	*Rede Eléctrica Nacional* (Portuguese TSO)
RTO	Regional Transmission Organization
SANPE	*Segurança de Abastecimento ao Nível da Produção de Electricidade* (Security of Supply of Electricity Production)
SEE	Strategic Environmental Evaluation
SP	Spatial Planning
SRG	Special Regime Generation

TEP	Transmission Expansion Planning
TN	Transmission Network
TSO	Transmission System Operator
VHV	Very High Voltage

Chapter 1

Introduction

1.1 - Project framework

This project focuses on the strategic planning of the power transmission network: the selection of the best alternatives for the appropriate design of the network expansion plan.

The work developed follows on the latest Transmission Network planning exercise performed by the Portuguese TSO – REN: Rede Eléctrica Nacional, SA - and addresses the strategic planning of the power transmission networks (mid-long term). More accurately, the Portuguese case will be detailed and will serve as a basis for this study.

Starting from a previous process of strategic formulation, this exercise will consist of an evaluation of the strategic planning for the network expansion.

The Basis of this study is the PDIRT 2009-2014 (2019): "Plano de Desenvolvimento e Investimento da Rede de Transporte" (Investment and Development Plan for the Transmission Network, 2009-2014 horizon). This document was elaborated by REN and its analysis is presented afterwards. The intent of this work isn't to rectify or replace that document but to gather all valuable work it presents in order to develop a formal multi-criteria model for decision aiding.

As the electric networks are in constant change, it may seem obvious that the continuous evolution of society leads, in technical terms, to the need of improvements in the electrical systems so that they can be able to perform their primary goal: supply demand (with adequate quality of service). On the planner's side, it comprehends an adequate adjustment of algorithms and techniques towards the meeting of new challenges.

Modern challenges that come up with the natural need for development and expansion of the electric networks compel the electric system agents to search for the best alternatives for its convenient development.

The work here presented seeks the analysis of the current Transmission Expansion Planning procedures/formulations and the formalization of the expansion process as a multi-criteria decision problem, being that the selection of strategies and, consequently, expansion alternatives takes into account several criteria – technical, environmental, etc. It objectifies a review over the Portuguese TEP methodology and criteria, proposing an aggregation model towards the clarification/simplification of the strategic issues that concern the TEP problem.

The application of a decision support methodology is intended, which is useful to the decision-making process to cope with the underlying constraints and criteria.

In response, a decision support system, capable of collecting information and organizing it preferably, as a multi-criteria strategy evaluation system, will be developed.

Among a pre-determined range of satisfactory expansion plans, the decision support system approach will be suggested in order to help the decision-maker in choosing the alternative that best suits the laid down objectives – optimality pursuit.

Summarizing, the objectives of this work are:

- Presentation of a framework regarding the Transmission Expansion Planning subject;
- Analysis of the Transmission Expansion Planning procedures carried out by the Portuguese TSO – REN - in the latest planning exercise;
- Formulation of the strategic planning problem as a multi-criteria problem;
- Development of a decision-aid methodology to cope with the multi-criteria strategic planning problem and consequent concretion by a Decision Support System.

1.2 - Transmission Expansion Planning

The Transmission Networks play a vital role in the electric system organization: they bond the generation and distribution sectors of the electricity market and also provide a "non-discriminative and reliable environment to suppliers and demanders"[1]. They assure the flow of electric energy from the power plants to the distribution networks (except in some cases of large consumers that are directly connected) and when often interconnected with the neighboring grids allow useful energy trades.

Many changes have occurred in the organization of the electrical systems over time. The unbundling of electrical systems gave them their present structure; it lead to the definition of the electrical transmission activity (that is often associated with the system operator activity), in most cases as a regulated monopoly.

"In regulated environments, a vertically integrated utility must serve its customers with an acceptable degree of continuity and quality, as economically as possible".[1] The expansion planning is, then, based on predictions: load demand forecasting, coordination with the generation expansion and potential unavailability of system components due to outages (scheduled or caused by failure).[2]

The Transmission Expansion Planning (TEP) becomes more complicated in countries where the energy market has been liberalized; the Transmission Network assumes a natural monopolistic position in the energy systems' structure (due to economic, technical and geographical reasons.), being, in most cases, leased to single entities and is opened for use by all eligible market participants under the so-called open access regime, which has greatly transformed the traditional power industry. It proves being a more challenging issue.[3]

The grid open access can lead to a greater benefits achievement as the actors in the power market tend to innovate and improve efficiency.[4]

Thus, this changed scene provides a significantly more uncertain background for transmission planning. Future generation, more than demand, is a particularly unsettled factor (new generation sites are determined independent of the transmission system) and is, therefore, the main driver of transmission development. Power station size, geographical location, load factor and the timing, all critically affect the performance of the transmission system.[5-6]

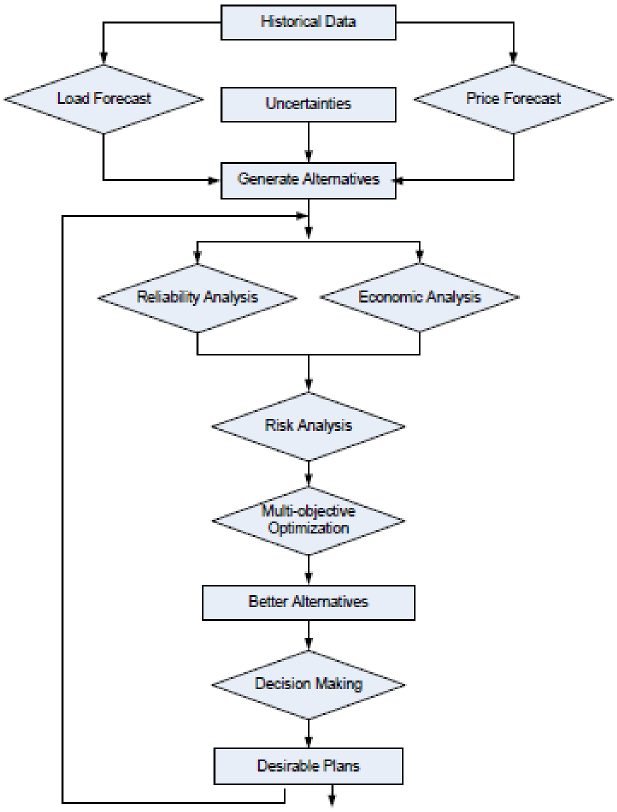

Figure 1.1 - Transmission Expansion Planning procedures in a deregulated environment - source: [4]

The process of generating expansion alternatives has to take into account the uncertainties concerning generation expansion and load growth, among other factors. In addition to technical impact assessment on system reliability, economic impact assessment on all market participants in the restructured environment becomes necessary,[3, 7] unlike the traditional regulated power systems where planners didn't use to worry about how to cover transmission expansion investments.[4]

In other words, transmission investment can be managed by monopoly management and market driven transmission investment while transmission planning can be managed by analytical tools which should have the ability to perform economic assessment and technical assessment.[8]

In Portugal the liberalization process took place, in a phased manner, between 1995 and 2006 (in compliance with the directive nº. 2003/54/CE). From this point on (September 4th of 2006) all electric consumers were able to choose from the last resort supplier (EDP, Serviço Universal [there are also some minor/local last resort suppliers]) to several licensee market suppliers (EDP Comercial – Comercialização de Energia, SA; EGL España S.L.; Endesa – Comercialização de Energia, SA; Galp Power SA; Iberdrola SA; Union Fenosa Comercial, S.L.).[9]

Like any other activity that bears economic importance, it is relevant that the growth of the Networks is conveniently planned, as there are infinite ways of proceeding to its development/expansion several factors have to be taken into account in order to achieve an effective good result in those planning exercises. Not only do technical constraints play, here, an important role, but also the environmental and economic factors are of extreme importance: a compromise between the robustness of the expansion plan and the costs must be achieved for efficiency in planning.

The goal is to minimize the network construction and operational costs while satisfying the demand; by other words, the traditional least-cost planning gives place to what may be referred to as cost-effective planning.[4]

Although the main slice of capital investment in the electric energy sector belongs to the distribution network, considering that even in developing countries, where the share of the Transmission Network is much bigger than that in the most developed ones, the fact that just a small percent of transmission expansion investment could be conveniently spared by adequate expansion planning, represents, definitely, a large amount of investment that can be redirected to other needs.

In the restructured power market it is evident that Transmission Network Owners/Investors are more interested in maximizing their own profit than in social welfare[10]: they not only consider the costs but also the possible return of the investment. Moreover, according to M. Lu et al[4] "the ratio of benefit/cost is a significant planning index in a market environment". As a result, transmission planning should still be controlled or regulated by a governmental organization or a regulator.

Moreover, in regulated environment, the planners have full access to specific information for transmission planning (eg. Generation costs). On the contrary, transmission network owners or investors have only general information, such as load demand, in deregulated market.[1]

Summarizing, the objectives of the network expansion should be [5]:

- Achieve economy and compliance with the planning standards;
- Facilitate competition;
- Allow flexibility for other outcomes;
- Avoid unnecessary investment – maximum utilization of the existing systems.

TEP can be performed by different types of entities such as governments, RTOs, TSOs or ISOs.

Since transmission planning is the key to keep the power system capacity ahead of demand fulfillment and a transmission system is built for an expected life that ranges 20-40 years, "transmission system investors have to pay the fiddler of their decisions for a very long period"[11]. Therefore, the investment decisions are the core of the TEP.

The plan flexibility plays an important role because it conceals the adaptation to changes in an uncertain environment and helps the investors to prevent from unexpected insufficiency.

Knowing that prospection of the future grid conditions, which are in constant evolution, towards problem identification serve as basis for these studies, minimum planning frequency has to be stipulated: TSO's typically elaborate new expansion plans from yearly to two or three-year-long periods.

This planning exercise isn't easy at all. It can be understood as a (combinatory) multi-criteria non-linear problem. J. McCalley et al[12] describes it: "It unavoidably includes a great deal of stakeholder input, human interaction and subjective decision, and it is impractical to look for a single software application to provide the transmission planning solution". Nonetheless, the human decision-making may be supported by a software application or mathematical formulations.

One way of looking into the network expansion problem is mathematical formulations: the transmission network expansion problem may be tailored upon mathematical models, which can present possible solutions (either good or optimal).

There are many mathematical approaches, some based on heuristics and, mostly, on meta-heuristics like simulated annealing, taboo search, genetic algorithms, but also evolutionary algorithms, linear programming, etc. There are also hybrid formulations, which merge characteristics of various approaches (eg. fuzzy decision analysis). Some of these approaches will be addressed below in a summarized way, with the purpose of framing this type of formulations.

It is also important to pinpoint that there can be several possible approaches to the transmission planning problem like line adequacy[13], voltage level stipulation, coalitions and expansion game theory[14-16], structure placement or transmission control planning[12, 17] but this study steps aside that.

In this study only Mid-Long Term Expansion planning will be considered being that short term expansion planning has a time horizon from three to five years and, commonly, addresses issues like reactive power management, voltage supply quality and transmission line congestion relief.[18]

As expressed above, the expansion of the Transmission Networks is a needed process due to the continuous dispersion of production, the increasing energy demand and the consequent need of adequacy for network reliability. Therefore, having a good expansion plan is essential.

This process has several stakeholders: besides the organizations which are actors in the power markets/power systems (such as load serving entities, independent power producers, interconnected transmission owners, etc.), the government, the populations and municipalities must, also, be targeted; that is why it is common to include a public consultation phase within the process, including various entities.

Besides that, there are many aspects that affect the Networks Expansion, from natural spatial planning to obvious economical factors. Many are the parts involved in all this expansion process and the fact that it has to obey certain legislation and evaluations (technical, environmental, etc.) makes it arise as a complex and longstanding process.

One of the core issues is the Environmental impact that this development inflicts. When considering the quality of local environment and landscape, new power lines construction should be avoided. But when global warming is considered, strengthening of the grid is required for acceptance of renewable energy generation. This and many other issues can be understood as variables that compose this multi-criteria problem.

1.3 - Portuguese Transmission Network

The Portuguese Transmission Network was leased to REN by the Portuguese government in an exclusivity (public access) regime. This encompasses the planning, operation and maintenance of the Transmission Network and also the global management and planning of the National Electric System.

Its mission is described as: “providing the uninterrupted supply of electricity (and natural gas) at the lowest cost, satisfying the quality and security criteria, keeping balance between supply and demand in real time and ensuring the legitimate interests of the market actors, conjugating the missions of system and network operator”.

REN is a member of ENTSO-E, the European Network of Transmission System Operators for Electricity, which is an association of 42 TSO's from 34 countries. Its mission is "to promote important aspects of energy policy in the face of significant challenges: Security, Adequacy, Market and Sustainability".[19]

This association aims at being the "focal point" for cooperation, both regional and Europe-wide, and coordinated work between TSO's, EU institutions and national governments contributing to improvement in energy policies, technical issues and for a "seamless pan-European Energy Market".

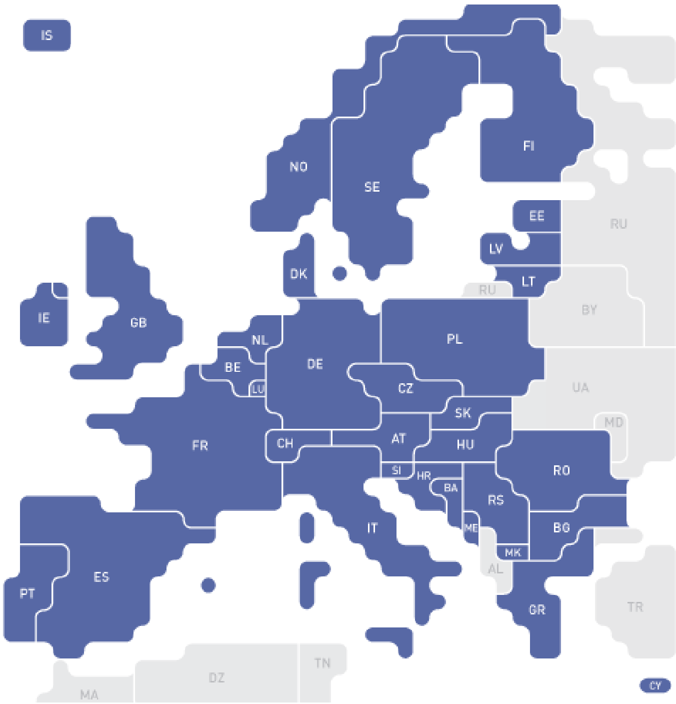

Figure 1.2 - Map of ENTSO-E member countries - source: ENTSO-E.

The Portuguese TN is almost all constituted by aerial power lines, connecting 44 electro producing centers (50% hydro plants, 16% Thermal and 34% special regime centers) and 83 installations, totaling about 7570 kilometers comprised in three voltage levels: 400kV, 220kV and 150kV.

The TN covers all continental territory as is depicted in the Network map presented in annex A.

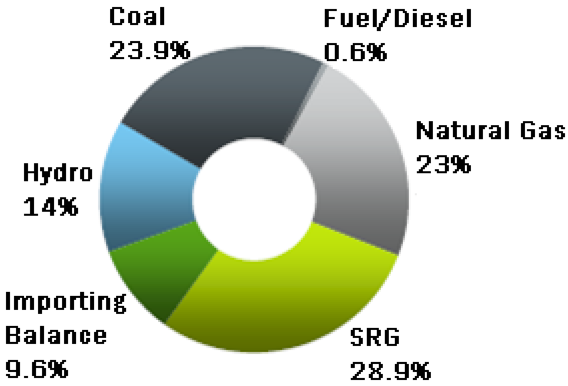

Figure 1.3 - Energy transmitted to the network, by type – source: REN.

The installed generating capacity in Portugal rounds 17000MW and the total consumption supplied reaches about 50TWh, from which only 9TWh corresponds to liberalized market costumers' consumption.

It possesses 28235MW of transformation power and is interconnected with the Spanish grid (REE) in eight points. That interconnection assumes great importance for the electric system operation, not only by trade purposes (MIBEL) but also by being a means of mutual relief between the two Iberian grids (and allowing the connection of the Portuguese transmission network to the rest of the ENTSO-E network).

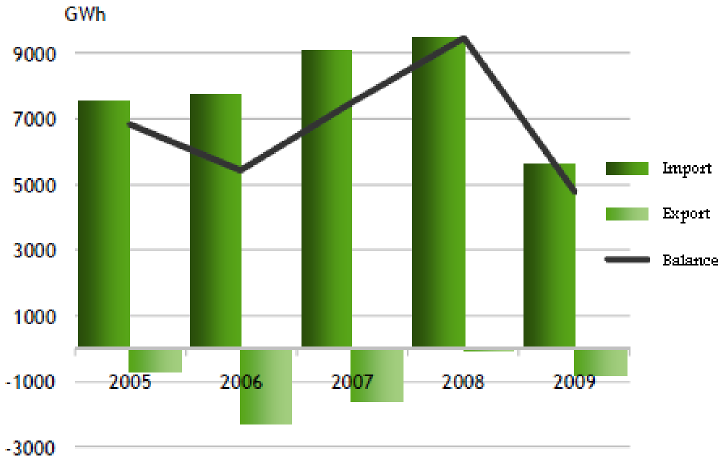

Figure 1.4 - Power flow in the interconnections – source: REN.

The Portuguese TN achieved a high baseline in terms of operation reliability and continuity and quality of service, in line with its best European counterparts.

REN classifies their action as a result of adequate policies and maintenance strategies, such as the efficient use of human and technical resources in the Network operation, an adequate planning in new infrastructure building and the renewal of the older lines and substations.

As the expansion and development of the Transmission Network are drawn upon a planning procedure, these issues will be addressed along with this document.

The data presented was made available by REN, on their website[20] being the most recent from December of 2009.

1.4 - Dissertation Structure

The work developed began with a study on the TEP issue with the purpose of better understanding and framing this subject.

Then, following the distinction presented above, in terms of possible approaches to that subject, chapter two addresses the mathematical methods for network optimization in an attempt of framing that matter towards a better comprehension of the thematic comprised by the Network Expansion processes. It isn't intended to present optimization methods but to provide a framework for decision-aiding, formalizing the strategic planning problem (and contributing to the decision-aid process).

In chapter three the document that serves as a basis for the Portuguese TN expansion – PDIRT – is presented with both an overview of the document and its constituents; following an analysis targeting the expansion planning subject.

Chapter four addresses the TN expansion issue establishing some parallels between the Portuguese case and the planning practices of other counterparts.

In chapter five the proposed approach is presented: the establishment of a decision support methodology for dealing with the formulation of transmission expansion planning as multi-criteria problem (the modeling and concretion of a DSS). The developed interface is also presented, with an example.

Chapter six presents the conclusions resultant from the work developed in this thesis.

Chapter 2

Mathematic Methods for Network Optimization

Many are the existent studies that cover the TEP issue by addressing mathematical approaches.

Traditionally, TEP algorithms are least-cost planning. Many research works have been done to reduce the computation time or increase the convergence towards true optimal solutions. After the power system deregulation, they have to be changed so as to handle the uncertainties (appearance of new challenges) as well as minimize total cost and maximize profit.[1]

Due to the increase in uncertainties (described as “randomness with unknowable probabilities”[4]) that the worldwide energy market restructuring inflicted, market-based approaches are the most common among expansion algorithms: financial and engineering analysis are incorporated. This led to an increase in investigation of Transmission planning.[21]

The pioneering Chilean and English systems experience in that subject pointed out that both models and algorithms should be reviewed in order to stimulate efficient investments – system optimization.

Some works in this matter - market-based approaches - have been developed centered in several methods, from which some may be cited:

H. Chao et al[22]. proposed the achieving of balance between economic structures and system reliability through the use of Monte Carlo simulation process for reliability performance and economic impact determination and basing, then, the expansion by assessment of some indexes – LOLE (loss of load expected), EENS (expected energy not supplied) and LMP (local marginal price).

M. O. Buygi et al [23] presented some step-by-step market based transmission planning approaches: using a probabilistic tool for random uncertainties modeling and selecting the final expansion plans either by fuzzy risk assessment, using a probabilistic tool for solving probability density functions of nodal prices or according to stakeholders' desires by risk assessment.

Hong Fan et al [24] use a bi-level programming model. A hybrid algorithm (genetic algorithm/primal-dual interior method) is used to solve the multistage TEP. In an upper level the goal is to maximize the profit of transmission system while in a lower level it's the maximization of social welfare (minimization of social costs).

M.R. Hesamzadeh et al [25] suggest a mathematical formulation based on the leader-followers game for transmission augmentation, considering the efficiency and competitiveness of the electricity market. This model, using Nash equilibrium equations, maximizes the profit of generation companies through a bi-level programming problem and models the market management company economic dispatch by linear programming, being solved by the revised simplex method. "The methodology can design the future transmission system not only for improving the system social welfare but also for encouraging competition among horizon year generating companies".

Apart from market based approaches, meta-heuristic optimization approaches, such as Genetic Algorithms, Chance Constrained Programming, Expert Systems, Fuzzy-set Theory, Pareto-based solution technique and Simulated Annealing have been proposed to solve TEP problems.[1]

Although there are still some approaches to meet the new challenges there is one issue still deserving adequate development: the incorporation of environmental impact measurement throughout the whole expansion operation algorithm.

The transmission planning can be divided into two types, depending on the treatment of the study period[26]:

- Static expansion planning:

Determine new structure sites and types for a minimum cost, taking into account load profiles for each planning period - finding the final optimal network state for a future single definite situation (static situation).

- Dynamic expansion planning:

Also determines when the structures to be placed/installed along a planning horizon. Leads to very complex and large problems and has excessive limitations concerning the systems modeling complexity.[21]

As many of the traditional methods still serve as basis for solid transmission expansion approaches development, here some examples of the most mainstream approaches are presented.

Table 2.1 — Synthesis of TEP mathematic approaches.

<table>
<tr><td rowspan="17">Static Methods</td><td rowspan="6">Math. Optimization</td><td>Linear Programming</td><td>[13, 27-30]</td></tr>
<tr><td>Non-Linear Programming</td><td>[31]</td></tr>
<tr><td>Mixed Integer Programming</td><td>[32-36]</td></tr>
<tr><td>Mathematical/Hierarchical Decomposition Techniques</td><td>[37-40]</td></tr>
<tr><td>Interior Point method</td><td>[41]</td></tr>
<tr><td>Branch and Bound</td><td>[42-43]</td></tr>
<tr><td rowspan="4">Heuristic</td><td>Overload Network – Transportation Algorithm</td><td>[27-28]</td></tr>
<tr><td>Investment/Operation Decomposition</td><td>[44]</td></tr>
<tr><td>OPF: Primal-Dual</td><td>[45]</td></tr>
<tr><td>Sensitivity analysis</td><td>[46-48]</td></tr>
<tr><td rowspan="6">Meta-Heuristic</td><td>Genetic Algorithms</td><td>[4, 49-52]</td></tr>
<tr><td>Simulated Annealing</td><td>[53-54]</td></tr>
<tr><td>Taboo Search</td><td>[55-57]</td></tr>
<tr><td>Expert Systems</td><td>[58-60]</td></tr>
<tr><td>Evolutionary Strategies - EPSO</td><td>[61]</td></tr>
<tr><td>Fuzzy Set Theory</td><td>[62]</td></tr>
<tr><td colspan="2">Hybrid Methods</td><td>[63-65]</td></tr>
<tr><td rowspan="5">Dynamic Methods</td><td rowspan="3">Math. Optimization</td><td>Linear Programming</td><td>[66]</td></tr>
<tr><td>Non-Linear Programming</td><td>[12, 67]</td></tr>
<tr><td>Dynamic Programming</td><td>[7, 68]</td></tr>
<tr><td rowspan="2">Meta-Heuristic</td><td>Genetic Algorithms</td><td>[26, 69]</td></tr>
<tr><td>Hybrids: Genetic Algorithms/Taboo Search/Simulated Annealing</td><td>[70]</td></tr>
</table>

The main concern of traditional methods is to identify power corridors that may become part of the expanded system, mostly, by employing the DC power flow method (which satisfies the basic conditions for the operations).[71] In some cases, loss of load may be evaluated with the purpose of penalizing the objective function.

Still, there are some recent studies on composite generation and transmission planning, besides the separation in planning of both areas due to the unbundling processes. They seek balance for both generation and transmission planning, considering that the adequate transmission network access and availability is the key for generation companies to thrive in the competitive energy market, independently of their disperse siting.[72]

Therefore, as cost allocation in a competitive environment is a key issue to be taken into account in a competitive environment, there is the need for developing methods capable of producing optimal solutions and to deal with the, dimensionality issue of the transmission expansion problem (huge networks study).

Some approaches will be briefly presented below.

2.1 - Linear Programming (LP)

Linear programming is used for network analysis targeting capacity shortages determination and relieving.

L. L. Garver[27] was a pioneer using LP for network estimation towards a near-minimum circuit miles network which has two steps: linear flow estimation and new circuit additions selection.

The problems are formulated as power flow linear minimizations - Linear Programming is used to determine the flow patterns that minimize the loss function; "overload paths" are then used for selection of circuit additions.

Garver proposed a constructive heuristic algorithm for the transportation model: a relaxed DC model, where some constraints are omitted.

This transportation model is used in the second step for the selection of new circuits.[71] It is formed by elimination of the Kirchhoff's second law constraints, in the DC model, which yields an equations system like this:

$$Min \quad v = \Sigma\ c_{ij}\, n_{ij}$$

$$\begin{aligned} s.a. \quad & S f + g = d \\ & |f_{ij}| \le f_{ij\,max}\,(n_{ij} + n^{\circ}_{ij}) \\ & 0 \le g \le g_{max} \\ & 0 \le n_{ij} \le n_{ij\,max} \end{aligned}$$

$$n_{ij} \text{ integer; } f_{ij} \text{ unbounded}$$

Figure 2.1 - Transportation Model formulation - source:[73]

Stated in the previous equations is the objective function that reflects the costs that are meant to be minimized: the branch addition cost - cij – for each nij - the number of new circuits in the i-j branch. The restrictions refer to Kirchhoff's first law and operational constraints (d: demand; g: generation; f: flow; S: node-branch incidence matrix).

2.2 - Branch and Bound method

In the example [42], Transmission Networks are modeled as transportation networks (like in the previous example) and the problem is solved decomposing into master and slave sub-problems (Benders decomposition).

The master sub-problem models the investment decisions and is solved using a branch-and-bound algorithm, while the slave models the network operation and is solved using linear programming.

In order to improve/reduce the computational effort required for solving the problem, Benders cuts are used, which represents a good approximation, relaxing the problem constraints; the exchange of information during the resolution process elapses as follows: the slave problem receives information about the investment decisions and, in reverse, relates the transmission capacity needs. Hence, for each solution "proposed" by the master, the slave evaluates it sending the corresponding feed-back.

The decomposing consists in solving the problem in a hierarchical, two-stage way:

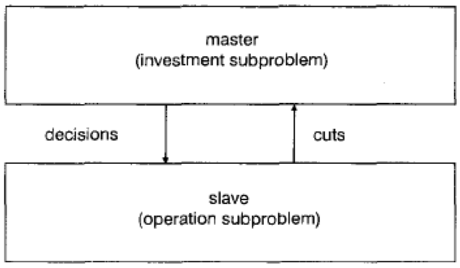

Figure 2.2 - Benders decomposition - source:[42]

The branch-and-bound algorithm "enumerates all feasible integer solutions" so that an optimal one can be found among the solutions space. The problem is partitioned in a set of sub-problems, in a tree structure, so that each can represent a possible candidate. The next step is defining upper and lower bounds for each node being that the downwards movement along the tree represents less cost solutions and more constraints decisions.

When searching for promising solutions, when a branch is rejected over another, its sequent nodes are all discarded. The constraints added represent properties of the power grid and the nodes (feasible solutions) represent possible circuit additions.

2.3 - Taboo Search (TS)

This Meta-Heuristic is efficient in solving combinatorial problems, such as the TEP. The way it's called comes from the fact that this procedure rejects already visited solutions labeling them as taboo (rejecting for a number of iterations) whereas the most attractive solution neighbors are evaluated after the desired "cost" function.

It's an iterative search that moves between possible solutions, in a defined neighborhood structure, searching for the biggest improvements towards the best solution. Intensification and diversification are some features of this method. They are related to search methods: diversification as searching for solutions in unexplored areas, while intensification is the exploitation of areas where better solutions may exist.

One of the fundamentals of this method, besides movement, is memory. Gathering knowledge during the search process allows to profit from it by escaping local optimal points. A Taboo List is created with the purpose of registering the information.

The management of the Taboo List is an important issue, since its size conditions the achievement of better solutions (preventing cycles). Another important aspect is the definition of a convenient movement strategy: departing from a solution, the neighborhood structure is composed by the set of solutions obtained by swapping circuits/lines or re-linking paths (except the ones labeled previously as taboo).

Another particularity is the definition of an aspiration criterion: at certain points, it allows the override of a taboo movement when it may be considered as interesting, potentiating the achievement of better solutions (more flexibility) through the overcome of local optimality points.

This method has proven to be a useful tool for determining the best expansion planning alternatives since it can handle quite well with a large number of possible scenarios, in an effective way, like expressed above, avoiding local optimum points.[57]

2.4 - Simulated Annealing (SA)

This Meta-Heuristic has its foundation in thermodynamics, more accurately, in the physical process of progressive materials cooling until a solid achieves the state of minimum energy, which grants more hardiness. It can be used for solving minimization problems whereas the objective is looking for a state with the lowest energy (lowest cost).

It's a probabilistic method: in every cycle (towards the least investment cost) of the algorithm through the neighborhood structure of possible solutions there's a probabilistic evaluation of acceptance of each point. The fact that the algorithm may accept at one point a solution that is worse than the previous, allows avoiding local optimal points.[74]

The transmission expansion problem is formulated upon which can be called a duality: (G, v)[54], where G is the space of solutions and v the cost function. The objective is to find, iteratively, the least-cost network configuration among all possible ones. This draws upon the fact that the cost function (analogously to temperature in the metallurgical processes) successively decreases over time.

Each iteration corresponds to a transition between the current configuration and another in the neighborhood. Those transitions may be achieved through the randomized removal, addition or swapping of circuits.

Simulated annealing is considered an efficient method for solving large-scale transmission expansion problems whereas its performance in searching for the least cost configurations depends on the fine tune of the model parameters, by the decision maker (control parameter T – Temperature – and the annealing schedule). That means leading the algorithm search to better solutions by only analyzing a small portion of the large solution space.

2.5 - Evolutionary Strategies - EPSO

EPSO – Evolutionary Particle Swarm Optimization – is a Meta-Heuristic method that is inspired in the Biology of species evolution - Darwin selection. The progress of this method is promoted by the optimal knowledge derived from the social behavior of species swarms. It is characterized by three factors: inertia, memory and cooperation.

This is an auto-adaptive method in which the particles cycle through space in the search of the best/optimal point.

The evolutive and auto-adaptive mechanisms of this method, acting together, increase the probability of the algorithm to move towards the optimum. It is evolutive because each step is directed to achieve the best point and the auto-adaptive characteristic derives from the fact that the algorithm learns how to best redirect to achieve optimality and, to do so, it auto-adjusts its parameters.

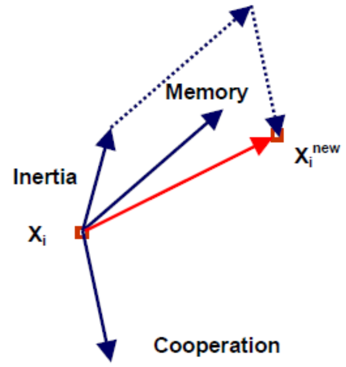

Figure 2.3 - EPSO particle movement principles – source:[75]

In the problem formulation, each particle is defined by its position and speed, which results from the interaction of the three movement principles stated above. This particle movement is responsible for generating new feasible solutions in each iteration.

This is a robust method for determining optimal solutions (min/max criteria) provided that its learning parameters, communication probabilities and number of particles are conveniently defined. In this particular problem, each point of the space represents a network configuration with its own cost value.

2.6 - Genetic Algorithms (GA)

This Meta-Heuristic, like the others presented, is inspired in a Nature process. Particularly, it is drawn upon genetics: evolution and survival of the fittest.

The first step is defining a convenient representation for the solution candidates. For example, R. A. Gallego et al [51] suggested binary, independent bits or decimal coding. As shown in the figure below, the possible solutions are concatenated, assorted in a chromosome-like way. Each shown portion represents the alleles of a possible gene (network configuration), conveniently coded.

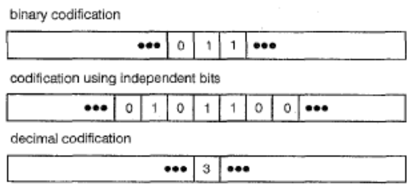

Figure 2.4 – Genetic Algorithm: different types of codifications – source:[51]

The most particular feature of this method lies in the sequence of generated populations (generations); it is due to three mechanisms: selection, crossover and mutation. They allow the creation of new generations with the purpose of clustering the "best genes" in an offspring, from which yields the desirable/best solution.

Along the process, after each generation of individuals, the offspring are evaluated by the objective (cost) function and the best are selected as the fittest. Then, they are chosen for producing the next offspring generation (through crossover and mutation processes).

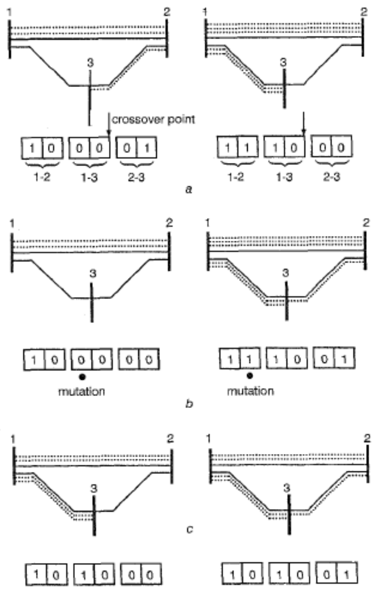

Figure 2.5 – Possible representation of a transmission system and new solution generation process – source:[51]

This Meta-heuristic is formulated as a maximization problem. Therefore, in the TEP case it leads to the need of transforming the typical minimization problem into the equivalent maximization one.

2.7 - Hybrid Methods

Every method has its pros and cons when it comes to solving problems with high complexity level, like the power networks expansion. In order to take a step forward, hybrid approaches have been developed with the purpose of developing stronger, more efficient algorithms that can combine the best features of several methods and merge them thus obtaining more powerful algorithms.[63]

Some examples are presented.

Katsuhisa Yoshimoto et al [65] presented an approach based Neuro-Computing hybridized with Genetic Algorithm, where the merits of both approaches complement their weaknesses. "The Genetic Algorithm is introduced into the generation of initial states for improving the solutions accuracy to be obtained by Neuro-Computing".

The authors consider that merging the Neuro-Computing capability of fast solution preparation and the Genetic Algorithm capacity of finding near optimal solutions results in an algorithm capable of achieving good results "within pratical time".

Hybridization of Taboo Search and a Genetic Algorithm is another approach and may depicted the following way:

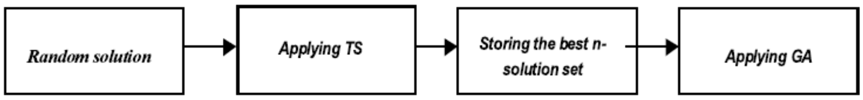

Figure 2.6 - Possible Taboo Search and Genetic Algorithm Hybridization – source:[64]

TS is applied as the search strategy and the "n best solution set" is stored for application of the Genetic Algorithm which will generate a new population, recursively.

Another possible approaches are the integration of Simulated Annealing and Genetic Algorithms, fuzzy logic and Genetic Algorithms or Simulated Annealing and Taboo Search[63], between many others

Hybrid methods may be able to solve both the static and the dynamic TEP problems and are promising tools for dealing with the networks expansion problem.[70]

2.8 - Conclusions

Mathematic methods for network optimization are an important facet of the processes underlying network development.

Even though some methods were presented and briefly characterized, only with the purpose of providing a framework on a possible way of addressing the TEP problem, these approaches aren't further explored in this work; since it was intended to broaden the study on the network planning activity, it may be concluded that these approaches hold great importance in the detail phase of construction of alternatives for the TN expansion, which is inseparable from the strategic planning.

From the study carried out, an important point to make out is that the current trend on the evolution of mathematic models corresponds to the development of hybrid methods

(methods that tend to incorporate the best characteristics of a set of others) which are the most able of presenting the best results (both in computational time and/or quality of the solutions).

Despite that, some of the other methods addressed, such as those based on Meta-Heuristics that are commonly inspired in Nature processes, have proven of being also effective and extremely useful.

Just to outline, an important aspect that concerns the TEP is the consequent development of specific software programs that aid the planners/analysts in their tasks. This represents the materialization of the mathematical formulations, applied to the TEP problem resolution. This is crucial in the planning exercise because not only the development of mathematic models but also the development of progressively improved interfaces, apart from greatly improving efficiency, allow aiding planners in reaching better expansion plans.

Chapter 3

PDIRT 2009-2014 (2019)

3.1 - Document Overview

The Portuguese TSO – REN – is the entity responsible for the concession of the Transmission Network. Not only its operation but also its expansion and development are under REN's domain (which includes the elaboration of PDIRT).

That document establishes the investments planned for the Portuguese Transmission Network development (DL 172/06). Every three years a new document is drawn. In this particular case, the document was produced in 2008 for the period 2009-2014.

As these types of projects aren't of punctual nature and comprehend a large conception length, there is some prediction of the future demands of the network expansion; in this case a "vision" of the network evolution until the end of 2019 is incorporated. This inclusion of a more expanded vision of the TN development horizon is justified by the need of indication of the most important evolution aspects, such as investments that will take place near the end of the 2009-2014 period that will, inevitably, extend to the following years. For the first 5-6 years the extensions and alterations to be made are specified.

Even though the period 2015-2019 is addressed in a less detailed way, the eventual future need for readjustment of those proposed investments isn't set aside.

PDIRT shouldn't be understood as a plan of exclusively new contents regarding its definition and implementation; it's the continuity of PIR 2006-2011 (and other older documents), which is an identical plan. That comes from the fact that, according to the legal regulations of TN planning procedures, the expansion plan must revised regularly (currently it's done every three years).

Identified as the most relevant objectives behind the PDIRT decision-making are:

- Ensuring all predicted demand covering;
- Availability for grid connection of high output plants (thermal and hydro);
- Ensuring conditions for reaching the national objectives in the Special Regime Production scope;
- Adequate interconnection capacity levels (MIBEL);
- Conservation or Renewal of obsolete equipments;
- Powering of high speed railroad lines (RAVE).

These goals may only be achieved while coping with an Environmental Evaluation (EE). That Evaluation is determined by law (2001/42/CE directive and DL 232/07) and will condition all of the planning process. REN identifies the possible routes/layouts that are, later, target of Environmental Evaluation by APA (Portuguese Agency for Environment). Then, DGEG (Energy and Geology National Entity) issues technical and administrative licensing.

The Environmental Report (ER) is the resulting document from the EE, also elaborated by REN along with this plan. Determined by law (DL 172/06 and 232/07) that document became now, for the first time, subjected to changes arisen from the public consultation process.

In the ER the analyzed strategic alternatives for TN evolution and the outcome (with the respective foundations) are described, which is presented and developed in this PDIRT. The whole EE process will be described in the next chapter.

The public consultation process that encompasses both the PDIRT document and the ER, which is established by law, involved several entities (more than 335 were contacted) from civilian governments and municipalities to environmental and regional development entities that amongst many others represent, by many reasons, the stakeholders of the Transmission Network Expansion.

From that public consultation process some technical alterations resulted which REN considered to be “pertinent to be adopted at the moment” and included them in the plan.

In this PDIRT four distinct strategic alternatives are presented and compared under a set of elements named as CDF (Critical Decision Factors), which are: Energy, Spatial Planning and Fauna. Taking, also, into account the perspectives of generation and demand evolution the choice for one evolution strategy results which agrees with the outcome of the EE.

The formulation of those alternatives, which will be discussed further ahead, was drawn upon some presuppositions contemplated in a document, also created by REN, called SANPE 2008-2030 – “*Segurança de Abastecimento ao Nível da Produção de Electricidade*” (Security of Supply of Electricity Production). It describes the evolution of electricity consumption, production facilities and special regime generation (SRG) assumed by REN.

The PDIRT 2009-2014 (2019) document, besides describing the objectives set for the Transmission expansion and the consequent EE, presents in detail the proposed investments and other technical information concerning the TN evolution which is briefly presented below.

3.1.1- Evolution of Consumptions and Means of Production

The perspective of evolution of the power generation system adopted was the "high scenario" contemplated in SANPE 2008-2030 Energy Policy.

An increasing mean growth rate of 4,3% is predicted, between 2009 and 2019, both for consumption and peaks. More information about this issue is presented in the table below.

Table 3.1 — Prediction of global electricity consumption (load factor for peaks=0,647) - source: REN.

Year	Final Consumption		Network Losses: TN+DN (2)	Supply (emission related values)	
	NES [GWh] (1)	Growth Rate [%]		Consumption (1)+(2)	Peak [MW]
2009	50645	-	4705	55350	9769
2011	55528	4.7	5158	60686	10711
2014	62899	4.2	5768	68667	12119
2019	76968	4.1	6967	83934	14809

Here, some important considerations are made: the most important variable, in what concerns TN sizing, is the peak consumption (mainly local peaks). Micro-generation, despite being able to achieve great significance in the future, isn't, for now, considered as a relevant sector in the energy system to account for.

Also, it's considered that a downward revision on the evolution of consumptions won't determine a change in the TN pre-determined evolution, except in timing.

The load forecasting present in the PDIRT elaboration consists of a statistical analysis of the production and consumption historical records, at each TN delivery point, and the forecasted growth rates provided by the Distribution Network concessionaire: "EDP Distribuição Energia, S.A.".

Concerning geographical dispersion, as expected, the majority of the electricity consumption is located in the coastal strip and the evolution of the peaks is farther more marked in the two biggest consumption centers: Lisboa and Porto metropolitan areas.

Relatively to production plants, the Energy Policy considered in SANPE 2009-2030 establishes both the decommissioning and the reinforcement/establishment of some thermal and hydro power plants.

Table 3.2 —New production capacity – source: REN.

	Thermo-electrical		Hydro-electrical	
	Combined Cycle	Coal	Reversible groups	Non-reversible groups
Nº.Groups	9	6	21	7
P (MW)	3528	2400	1882	646

The bet on reversible groups is the generalized trend since it leads to a considerable increase in the electrical system efficiency, from technical to strategic issues.

Table 3.3 — Plant decommissioning, by the type of groups – source: REN.

	Fuel	Diesel	Coal
Nº.Groups	11	1	4
P (MW)	1712	165	1192

This evolution of the Electro-producer system is outlined in the Energy policy scenario of the SANPE 2008-2030 with some subsequent changes, like the consideration of the hydro plants encompassed in the PNBEPH.

Another aspect to retain is the fact that the vectors determined for SRG are based mainly on the onshore wind energy production, assuming a clear increase in this energy type production targets.

Table 3.4 — Global SRG evolution by type [MW] – source: REN.

Type	2009	2011	2014	2019
Onshore Wind	4500	5500	6100	7500
Offshore Wind / Waves	-	-	-	550
Small Hydro	430	465	510	600
Cogeneration	1800	2050	2230	2590
Biomass	100	225	250	250
MSW	90	115	140	150
Other renewable sources	145	220	280	300
Totals	7065	8575	9510	11940

3.1.2- Interconnection Capacity

One of the objectives of this PDIRT is reaching the goal of 3000MW interconnection capacity that is also a political objective for both Portuguese and Spanish governments considered as essential for the Iberian Electricity Market (MIBEL) development.

Currently, the minimum interconnection capacity is about 1100MW towards importation and 1200MW towards exportation, while the mean capacity of importation is around 1300MW, during peak hours.

Due to outages/line unavailability those values may become reduced. That may cause the reach of the interconnection capacity, which induces market splitting. It's desirable that this situation is minimized to ensure the competitiveness between all market agents.

The goal is to achieve a capacity of 3000MW, which represents about 25% of the peak consumption predicted for the Portuguese electrical system (one of the highest interconnection capacity/peak consumption ratios in Europe).

That capacity is meant to be achieved mainly by the establishment of two new interconnection lines (Algarve-Andaluzia and the second connection Northeast Portugal-Galiza) and will potentiate the national electric system to become, in average, an average exporter, becoming the interconnection congestion periods rare (unless any unavailability of the electro-producer system occurs).

Those two interconnections also allow the accomplishment of other objectives, such as the support to the distribution networks and the acceptance of new generation.

3.1.3- Planned Investments

The investment values arising from the selected expansion plan are presented and discriminated for the 2009-2019 period.

In terms of Capital Expenditure, the total investment sum rounds 1440M€, which corresponds to an annual average of 240M€; value which is in line with the most recent previous years sums.

The specific investment (98% of total) is subdivided into two activities: Electric Energy Transmission (95%) and Global System Management (3%), from which the biggest share can be disaggregated:

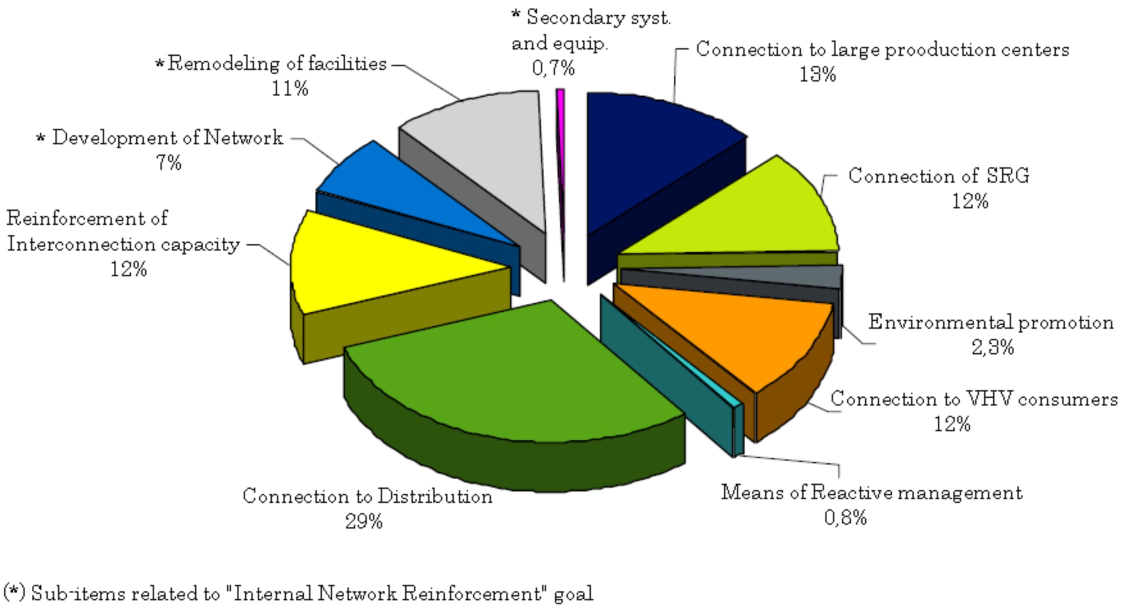

Figure 3.1 - Disaggregation of the Electric Transmission investments, per goal – Source: REN.

3.1.4- Characterization of the investments in the TN

The Investments presented in this PDIRT are divided by areas. That division does not correspond to an administrative division but results from the TN present (and future) structure and the proximity to considerably important production or consumption areas.

The considered areas are eight: coastal strip north from Porto; Trás-os-Montes and Douro axis; Porto metropolitan area; coastal strip between Porto and Lisboa; Beiras Interiores, Lisbon metropolitan area and Setubal peninsula; Alentejo; Algarve.

The objectives of those investments are:

- PRE connection;
- Connection of large production centers;
- Connection to Distribution;
- Connection of MAT end users;
- Reinforcement of the interconnection capacity;
- Internal reinforcement of the TN.

All relevant projects are presented in the plan and briefly described, along with the correspondent geographical location (through maps), like the new lines and substations.

3.1.5- Principles and Criteria for Planning

The technical criteria for the TN planning are set in the "Padrões de Segurança de Planeamento da RNT" document (security patterns for the TN planning) which was previously elaborated by REN and approved by ERSE.

Here some of the factors that REN takes into account for the TN expansion problem and that determine the planning options are described.

- ✓ Fault Currents and Network Loss Evolution

Some considerations about the fault currents and the network loss evolution are made; since the increasing network enmeshing, although allowing its more efficient operation, reducing power losses and increasing reliability, also leads to an increase in the short-circuit currents. This fact will require more robust equipment (and more expensive too) to be dealt with.

There are maximum values stipulated for the fault currents and REN will take into account their evolution when dimensioning new network structures, in order to keep them below the limits.

The loss management is included in the EE, since the energetic sector represents a share of approximately 40% of the effort proposed for the greenhouse effect gas emissions reduction and, consequently, upper bounds have been established for it.

- ✓ Reliability of energy supply

This is a constraint in the TN planning. Its assessment can be made by the comparison of the indexes established in the Quality of Service Regulation with the TN delivery points supply. It is fundamental for the TN adequate service that this constraint is always checked.

As an example, the introduction of differential protection functions to the TN lines has improved significantly the selectivity, avoiding some accidental protection triggering.

- ✓ Joint optimization with production and distribution

By performing technical and economic studies in the boundaries Transmission-Generation and Transmission-Distribution an articulation between the benefits and induced costs arising from the power system activity is sought.

A major example is the reinforcement of the SRG acceptance capacity, which has high goals established for this PDIRT.

- ✓ Remodeling of facilities

The oldest facilities (older than 40-50 years) require special attention because their equipments may be obsolete or represent a functional insufficiency. Therefore, to minimize their impact on the service quality and network reliability, remodeling is needed.

Not only does the replacement of equipments in the end of lifetime usage ensure the adequate system reliability but also may allow the implementation of new operation functions required by REN to correspond to the evolution of the electrical system.

- ✓ System Stability

The TN must keep a stable behavior with the occurrence of perturbations (dynamic and transient stability). REN establishes the technical requirements for generation groups, to ensure a stable and secure behavior, and performs network stability studies. In the TN planning process it allows the prediction of the consequences that major perturbations may cause.

The increasing number of network interconnections and network the enmeshment are decisive factors to deal with this issue.

- ✓ Environmental Impacts

This is the most determining issue that REN considers for the TN planning activity.

The reduction of the environmental impact that the proposed solutions inflicts may be achieved, during the planning phase, through the efficient reinforcement of existing power corridors and line adaptation for higher voltage levels or double configurations, avoiding when possible the construction of new corridors.

The remodeling of facilities and the replacement of obsolete equipments are other aspects to be taken into account for mitigation of the environmental impacts.

The process of Environmental Evaluation that concerns the assessment of the issues related to TN expansion and, due to its fundamental importance in the planning exercise, is conveniently described below.

3.2 - Environmental Evaluation

Because it belongs to the energy sector, the PDIRT is bound by an Environmental Evaluation, which is stipulated by law. The objective is to identify and assess the strategic options presented to the development of the Power Transmission Network, addressing the underpinning sustainability principles.

This is the first time in Portugal that the strategic options for the network development were weighted by an EE process.

The EE was started in July 2007 and its range was submitted to institutional consultation through the discussion of the Critical Decision Factors Report.

The PDIRT and its EE were developed simultaneously and complementarily, congregating together the underlying environmental, social and economical factors. Therefore, the EE is placed in a context of sustainability.

From the EE results an Environmental Report (ER) that presents the assessment of the environmental impact that each particular expansion alternative bears.

As mentioned above, those factors compose the need of this type of studies that copes with the planning work: therefore we can speak in terms of a Strategic Environmental Evaluation (SEE).

The methodic approach of the SEE ensures the compliance with the Portuguese law and is structured as follows:

- Integration with the TN planning process;
- Strategic impact assessment;
- Validation of the assessment and TN expansion plan quality.

It elapses in three main phases:

1) CDF identification and analysis;
2) Strategic impact assessment;
3) Elaboration of the Environmental Report.

The Environmental issues considered for the SEE result from an “interpreted reading” of the law requirements (ordinance 232/2007 from June, the 15th) and present as follows:

Table 3.5 — Environmental issues established by law – source: REN.

Environmental Issues in national legislation	Translation for PDIRT's SEE	CDF
Biodiversity Fauna Flora	Fauna and Protected Areas	Fauna Spatial Planning
Landscape Cultural Heritage	Landscape and Heritage	Spatial Planning
Climatic factors	Energy	Energy
Population Human health	Health and Populations Noise	Spatial Planning
Material goods	Urban Network and large Infrastructures	Spatial Planning Energy

The table above "translates" the environmental issues depicted in ordinances to the contextual reality of the PDIRT study. It is also referred that the following environmental issues weren't considered relevant due to not imposing any risk to the Power Transmission activity (at PDIRT's scale): Water, Atmosphere and Soil.

The Environmental Evaluation's range is determined by the choice of the CDF.

3.2.1- CDF – Critical Decision Factors

The CDF can be understood as "observation windows": they represent the strategic basis for the Network Expansion plan and appear structured in criteria and indicators.

Their selection resulted from an integrated analysis of the following elements:

- Strategic Reference Framework, which covers policies, plans and programs related to PDIRT.
- PDIRT's objectives and strategic guidelines.
- Legal Environmental policies within PDIRT scope.

These factors will structure both the strategic impact assessment and the SEE analysis and are bound to consultation by the entities with environmental responsibility (depicted by law).

The scenarios stated in PDIRT may be understood as the alternatives which will be targeted for a CDF based evaluation; its result will allow the establishment of environmental guidelines for planning and process monitoring.

Therefore, the SEE will address those alternatives and the technical options assessing the opportunities and risks in terms of environmental and sustainability issues. From here will result a set of indications that will be incorporated in the PDIRT development.

For a better understanding, the chosen CDF are presented below.

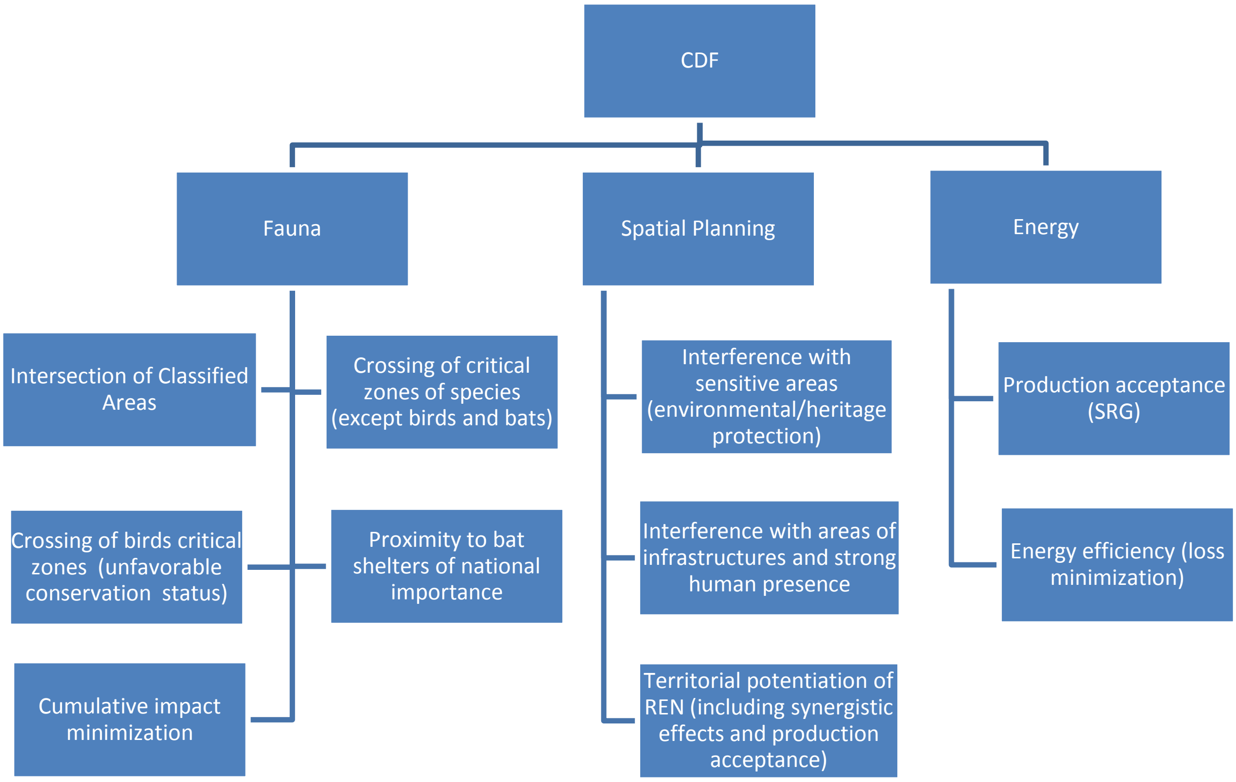

Figure 3.2 - PDIRT's CDF evaluation criteria.

The three CDF and their correspondent evaluation criteria and indicators are presented in Annex B, in detail.

3.2.2- TN Evolution Alternatives

In this PDIRT four strategic alternatives, with different potential relatively to two criteria, were developed: flexibility and SRG acceptance capacity.

In the EE those possible alternatives were considered for the TN expansion and are presented in the following table.

Table 3.6 — TN development alternatives proposed – source: REN.

	New SRG acceptance capacity	Flexibility
Strategy 1	Elevada (Very High)	Alta (High)
Strategy 2	Alta (High)	Alta (High)
Strategy 3	Média/Alta (Average/High)	Média (Average)
Strategy 4	Reduzida (Reduced)	Reduzida (Reduced)
Strategy F	Alta/Elevada (High/Very High)	Alta (High)

A brief description over each strategy is presented:

Strategy 1 - strategy further enhanced, with preferential use of existing routes, with all main lines designed for 400kV;

Strategy 2 - enhanced strategy, with preferential use of existing routes, with a significant number of new lines to lower voltages to 400kV;

Strategy 3 - enhanced strategy, with corridors covering some new areas, with all main lines designed for 400kV;

Strategy 4 - restricted strategy, in which only the minimum requirements to meet the guidelines of national policy for energy are considered;

Strategy F - strategy enhanced with new expansions developed mostly along existing routes, with all main lines designed for 400kV.

An additional expansion alternative, called F, was suggested after a first environmental and sustainability multi-criteria assessment, in which the Energy CDF was potentiated and the impacts related to Spatial Planning and Fauna CDF were mitigated.

That was the withheld alternative because it was considered to be the alternative that “globally minimizes the risks and maximizes the opportunities” and, consequently, is the one developed in this PDIRT. It is also marked that this alternative most enhanced elements are the preferential use of existing lines and prevision of high capacity lines at 400kV.

A summary of the evaluation is also presented:

Table 3.7 — Synthesis of the alternatives assessment – source: REN.

CDF	Criteria	Alternatives				
		1	2	3	4	F
Energy	Production acceptance, namely from SRG	++	+	+	-	++
	Energy Efficiency (management and reduction of network losses)	+	-	-	+	+
Fauna	Intersection of classified areas	--	--	--	-	-
	Crossing of species' critical zones	--	--	-	--	-
	Crossing of critical zones of birds species with unfavorable conservation status more susceptible to collision	--	--	-	-	-
	Proximity to bat shelters of national importance	--	--	--	--	-
	Cumulative impact minimization	-	-	+	+	+
Spatial Planning	Interference with sensitive areas (environmental/heritage protection)	--	--	-	-	-
	Interference with areas of infrastructures and strong human presence	--	--	--	-	+
	Territorial potentiation of REN (including synergistic effects and production acceptance)	+	+	-	-	++

Here, the five alternatives are assessed relatively to each criterion derived from the CDF's. The scale used ranges as: "++" - very significant opportunity; "+" – opportunity; "0" – indifferent; "-" – risk; "--" – very significant risk.

In this multi-criteria evaluation, the "F" alternative appears undoubtedly as the desirable. Although from the Environmental point of view that alternative dominates the remaining, when considering the other criteria, that circumstance couldn't be enough to support its selection.

A framing attempt is presented next, with the purpose of clarifying the decision-making behind this process.

3.3 - Document Analysis

As PDIRT's main issues were already presented some considerations may be drawn from its study.

The PDIRT document can be described as quite comprehensive due to presenting valuable information on subjects such as the TN expected evolution, the characterization of the planned investments and the EE process carried out. Also, the information (and data) on the network expansion is, geographically, well characterized.

Even though there is some dispersion on the presentation of both the fundamental objectives and criteria underlying this planning exercise, it incorporates the necessary elements for establishing a decision-aid multi-criteria model, provided that an adequate integration of the information is made.

The meshing between the presented objectives for the TN expansion and the planning principles and criteria isn't well evidenced along with the strategic objectives: they aren't distinguished specifically by constraints and criteria.

The CDF that ground the EE process, described as "the fundamental aspects upon which the SEE analysis relies", are three: Energy, Spatial Planning and Fauna. They are divided into evaluation criteria, totaling 10. On the other hand, REN established indicators individually for each criterion. Those indicators are meant to be the PDIRT's range for the strategic approach to the network development problem (presented in annex B).

Even though these are the criteria taken into account by REN, it is said that the use of others (without specifying), along the planning process, could be possible.

The main objective of the CDF assessment is, on the one hand, to identify which are the most problematic factors, liable of conditioning the expansion alternatives and, on the other hand, the identification of those that best suit the pursuit of the strategic objectives depicted by the Strategic Reference Framework. Therefore, their main intent is the minimization of the Environmental impacts caused by the TN development.

These CDF may be analyzed more closely.

The Energy CDF encompasses two evaluation criteria, in which energy efficiency and production acceptance are comprehended. Undoubtedly the loss management and minimization contributes significantly to greater benefit achieving in environmental terms. Even though it isn't directly embodied in a criterion, loss reduction leads to greater efficiency in network operation which leads to a reduction in greenhouse gas emissions. This is a very important issue since many goals and policies have been developed and established among the international community, as the Quioto Protocol or the EU "3x20 targets": that is a climate and energy policy that sets the "ambitious targets" for reducing greenhouse gas emissions in 20% and the increasing of 20% in the use of renewable energy sources and in efficiency. On the other hand, the more efficient the network operation, the lowest the costs will be for the end users.

This issue can be conveniently assessed by the prediction of the network losses for each alternative, since there are effective ways for it (network evolution forecasting and statistic analysis).

Regarding the production acceptance, the national energy policies have been focused in the development of renewable energy sources and nowadays the NES evidences high wind power penetration and the trend is to keep on enlarging the share of SRG in the global generation capacity. Even though there are established goals for SRG production acceptance, the higher the production decentralizing and acceptance capacity the more optimality in the system operation is, consequently, achieved. The establishment of an index of equipment usage in renewable energy sources production areas, as suggested, may be a good indicator.

Not only must the renewable disperse generation be considered for the network adequate generation acceptance levels, but also the possible future connection to new plants without the need of a major grid reconfiguration.

In the future, interaction levels between the TN and the Distribution may be delineated, as well as assessment criteria, with the purpose of following the trend of the creation of large intelligent grids. It can be seen on figure 3.1, the pie chart that presents the disaggregation of the investments, that “connection to Distribution” represents the biggest slice of the total investments - 29% - (which may state its importance).

Another aspect to be focused is the fact that the renewal/replacement of older equipments/facilities, which is pointed out as an objective for TEP, isn’t explicitly included in the EE. Even though it allows improvement in the system efficiency, it’s hard an aspect to quantify as a criterion.

From the analysis of table 3.7 it’s clear that this is the most potentiated CDF of the EE process. Despite being able to be considered as the one which causes less direct impact on the Environment, it is the most enhanced CDF, from which one can infer that the process of planning and strategic environmental assessment may have it as the main point.

The Spatial Planning CDF incorporates the Environmental impacts on the territory crossed by power lines or facilities. Those impacts are distinguished by heritage, nature, landscaping and cultural values.

The assessment of this FCD is centered on the determination of areas that are considered sensitive either by being specially classified as special protection zones or zones of strong human and infrastructural presence. Then, at a cartographic macro-scale which zones potentiate the network development and which ones condition it are determined. It’s obvious that the overhead line construction always inflicts negative impacts on Spatial Planning. So, this CDF is meant to be mitigated by the consideration of different zone classes for each conditioning factor and the accountancy of the number of overhead line corridor routes crossing occurrences.

Even though SP is assessed in a macro-scale and often its issues are under local/regional scope, the underlying methodology used by REN for its assessment may prove successful because it allows the determination of major territorial delimitations for the establishment of structures and the consequent design of possible expansion vectors.

The cartographic elaboration is set upon the collection of data provided from a wide range of entities with relevant importance in this context, such as Environmental Atlas (concerning geological, agricultural and natural reserve zones), military maps and other documents with information on regional development, major infrastructure locations and demographic data.

With regard to infrastructure placement, REN considers, as important evaluation criteria, the territorial potentiation: the possible recovery of existent routes of corridors in zones with existing power lines. Also, another used indicator is the production acceptance. Even though the generation decentralization was mentioned as an important issue that can be integrated in the Energy CDF, here it is presented again (when it could only be incorporated once).

The Fauna CDF is the one which presented worst general results in the strategies' EE. It incorporates five criteria, from which intersection of classified areas was already proposed in Spatial Planning. Even though they focus different specific subjects, the inclusion of the intersection of natural classified areas could easily be incorporated in the cartographic analysis referenced above for SP, meshing all territory constraints in a single analysis. Even though the process adopted by REN isn't fully described, it may be assumed as capable of providing feasible results.

The preservation of species, upon which the TN development and operation is susceptible to cause serious impact, must be ensured. Those species are identified, especially those characterized as of less favorable conservation status, and the extension of those species' critical zones crossings is, again, the determinant factor for this CDF assessment. Therefore the geographic locations of those species' shelters and migration corridors must be considered for an efficient planning.

The planning of placement of overhead power lines can be limited by the macro-scale analysis already depicted, and cannot always influence negatively those species' habitats. In these terms, special measures have to be taken into account not only in the planning phase but also in the construction/implementation of the structures phase, since the adequate management of the "barriers" placement relieves the total impact caused by planning of the power lines crossings.

As no consideration is made in terms of impact on Flora it may be concluded that the possible impacts regarding this issue could be considered in other phases of the TN expansion different than that of the planning.

Water, atmosphere and soil are factors dismissed by REN from the planning process by not considering them to bear significant impact. Indeed, physically, they aren't directly affected by the expansion of the TN, in a way that could jeopardize other environmental issues. If, perhaps, there is any issue underlying these factors that should be considered as soil or water preservation, it could easily be incorporated in the SP criterion.

A research concerning other TSO's Transmission Planning activities was developed, in an attempt of establishing a comparison with the Portuguese case.

The search for new "major" planning criteria/indicators that could be incorporated among the CDF (as suggestions or complements) was unsuccessful since either the used criteria for TN development by other TSO's were already considered by REN in this PDIRT (vast-range criteria) or the internet/scientific database research couldn't reach the core of the strategic planning, unveiling other used indicators. Besides that, other TEP procedures are presented in the next chapter in a context of deepening the current study.

With respect to the EE process, four alternatives were presented for assessment. "As a result of active cooperation between the team responsible for the PDIRT elaboration and the EE team, an additional expansion alternative, called F, was suggested after a first environmental and sustainability assessment"[76], in which the Energy CDF was potentiated and the impacts related to Spatial Planning and Fauna CDFs were mitigated. Despite not being supplied much information concerning that first assessment, in fact, that results from an attempt of clustering the most significant opportunities of the four "primary" strategies in a new one. "F" is the expansion alternative that outcomes from the EE process and is the one considered and developed in this PDIRT document.

As expressed before, the process of generating new expansion alternatives isn't sharply presented, but it's mentioned that each alternative was "territorially analyzed and discussed"[76] taking into account some requirements (supply of predicted consumptions, integration and acceptance of production and international interconnection capacity); relatively to the number/quantity of presented alternatives, nothing is indicated about being in adequate number (so that the bigger diversification in characteristics could present better scenarios for the TEP exercise) or if there is the need for generating more alternatives so that the efficiency of the process could be enhanced.

PDIRT presents those five possible alternatives in a table (which is transcribed in table 3.6) where only two criteria are considered: Flexibility and new SRG acceptance capacity (where the first represents the "ability of being able to receive, without reinforcements (lines and substations), changes in volume and geographic location" and the second refers to the "acceptance capacity beyond the set targets on energy policy".

With respect to SRG acceptance capacity criterion, it may be noted that there is a repetition: it is presented at this level as a major criterion but then appears included in the Energy CDF, in the EE impact assessment.

Another aspect worth pinpointing is the fact that the classifications of the scale in use are, somehow, ambiguous. It isn't stated any information on the importance of the levels used (relative value of each).

It is unclear why the lack of connection or continuity between the two tables referred to: the several expansion alternatives appear characterized and classified only in terms of Flexibility and new SRG acceptance capacity and the Environmental Assessment is presented separately. Also, a structuring of the criteria in a hierarchical level is not visible.

Concerning the EE in table 3.7, each strategy is assessed by the defined criteria, may obtain the following classifications: "++"; "+", "0"; "-"; "--".

Here, two considerations can be made. First, each strategy is evaluated after each criterion, not being reached a global result/classification regarding, individually, the whole evaluation process. This means that a global result of the assessment of the ten designed criteria isn't displayed/achieved.

Then, the scale used doesn't translate information about the decision-maker choices/preferences accurately, as there isn't any kind of data about any possible difference between levels; in other words, it isn't depicted whether the variation in scale from "--" to "-" bears the same weight as the transition between "-" and "0" (and so on), that is, if some levels are "closer/distant" or "equally spaced" (linear scale) in terms of value.

From the close analysis of table 3.7 comes out the fact that no strategy is indifferent to any criteria (the "0" is never used) and that some criteria remain, nonetheless, heavily penalized (specially the criteria of the Fauna CDF). This depicts well the mitigating nature of the EE.

As a last remark from the document analysis, it may be emphasized that no information about the financial impact/costs arising from the concretion of each individual strategy is displayed. Its inclusion on the evaluation of alternatives process is suggested afterwards (chapter 5), as a reference criterion.

Even though the EE process isn't well stated in the document it can be inferred, without having the required knowledge in the subject, that it occurs in an efficient way, congregating a wide range of factors/criteria and that its implementation, along with the planning process fosters the compliance with the sustainability policies of the TSO.

From the analysis of this PDIRT results the formulation of a multi-criteria problem approach, whose modeling and concretion are described afterwards.

Chapter 4

Transmission Expansion Planning Practices

An overview over the TEP subject was already presented as well as the Portuguese case, which was particularly analyzed.

In the previous chapter, the Portuguese TEP process, which is carried out by REN, was addressed. Some conclusions have been drawn upon the analysis of the development and investment plan for the TN (PDIRT); more precisely, about the contemplated EE, that is a critical part of the TN planning process and has proven to be efficiently conducted.

Although this work was triggered by the latest planning exercise of the Portuguese TSO – PDRIT – it acquired a broader scope, specifically the study of other TEP procedures, carried out by REN's foreign counterparts, for both acquaintance with different planning methodologies and the search for additional planning criteria/indicators. That study was carried out through internet research of the contents provided by the various entities.

Some TSO's TEP procedures are here highlighted as mere examples, with the purpose of illustrating the broadening of the study carried out.

4.1 - PJM

PJM is a RTO that operates in 13 states and the District of Columbia in the (eastern) United States. This is a regulated company (by FERC - Federal Energy Regulatory Commission) that "operates the world's largest wholesale electricity market" and is committed to the planning and development of the TN.

It is responsible for the annual elaboration of the RTEP - Regional Transmission Expansion Plan - which identifies the needed grid improvements. Several studies are carried out to identify, at an interstate scale, "the most effective and cost-efficient improvements", coping with national and regional standards. Those national standards are stipulated by NERC – North American Electric Reliability Council.

Transmission Planning studies are conducted for a 15-year horizon and are based on regional power flows and forecasted system operation conditions. The upgrades then identified as necessary are assessed in terms of their "feasibility, impact and costs, culminating in one plan for the entire PJM footprint". This process is carried out in strict collaboration with committees establishment and with the several stakeholders: Transmission Owners, regulators etc.

The Regional Transmission Expansion Planning process is schematically presented below:

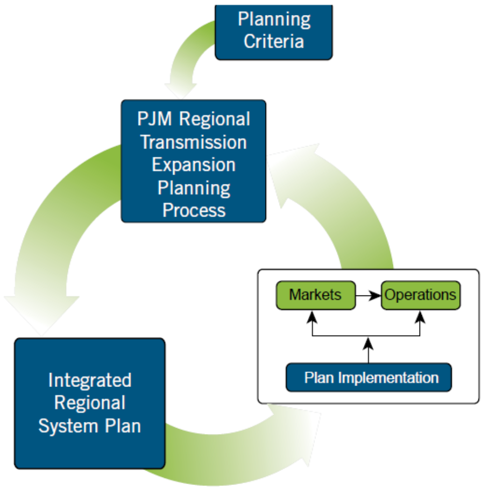

Figure 4.1 - Regional Transmission Expansion Planning process – source: [77]

The planning criteria are the standards by which the needed improvements are identified; they are defined by NERC and the Transmission Owners. In the mentioned report, only criteria of technical nature were presented.

At a regional level, the creation of committees with the purpose of raising planning issues and discussing the proposed upgrades is important for defining a development baseline.

Several possible improvements are studied and addressed to the integrated system planning that is composed by "four paths: reliability, economic, interconnection and local planning", until a final plan is achieved (RTEP) and approved by the PJM independent governing board.

The cyclic process depicted above illustrates how the several stages take place and have influence in the TEP activity.

There is no information available about environmental or spatial planning assessments during the planning exercises – only reliability/technical criteria are referenced. From this, it may be concluded that either the impact measurement only occurs at a technical level or the other impacts are assessed at a regional/local level.

Also, it comprehends a large opportunity for stakeholder input, since there is frequent exchange of information between entities along the annual planning cycle.

The resulting expansion plan is then addressed to the several Transmission Owners that are compelled to the concretion of the established enhancements, being a highly market-operative oriented process.

4.2 - REE

Red Eléctrica de España is the Spanish TSO and operates the electricity transmission activity on an exclusive regime.

El Ministerio de Industria, Turismo y Comercio – MITyC - (Commerce, Tourism and Industry Ministry) is responsible for the approval of the Electricity and Gas planning document: its current version refers to the 2008-2016 horizon and contains the description of the stipulated investments infrastructures and expected costs. This type of document is drawn every four years and its main objectives are such as the network meshing reinforcement, support for the high speed trains powering, and the reinforcement of the international interconnections. All this has the goal of increasing the TN reliability and ensuring higher system efficiency so that the electricity market is potentiated.

The Spanish government, by considering the energy sector as absolutely essential for the country adequate development, brings together the planning of the TN, binding to all market agents. This planning is developed along with the TSO strict cooperation and under the CNE (National Energy Commission) supervision.

REE elaborates forecasting studies concerning electricity demand and supply, estimation of consumptions and peaks and assesses the adequacy of the system installed generating capacity with the objective of guaranteeing “the right balance of safety and reliability for future electricity supply, under the following criteria: financial efficiency and utmost environmental friendliness”.

This process takes largely into account sustainability issues: a strategic environmental assessment is conducted with the purpose of guiding the planning, since its beginning, to cope with matters like the gas emissions reduction and the network integration of renewable energy. Also, the environmental assessment is depicted by law and its integration with the TN planning process is illustrated below.

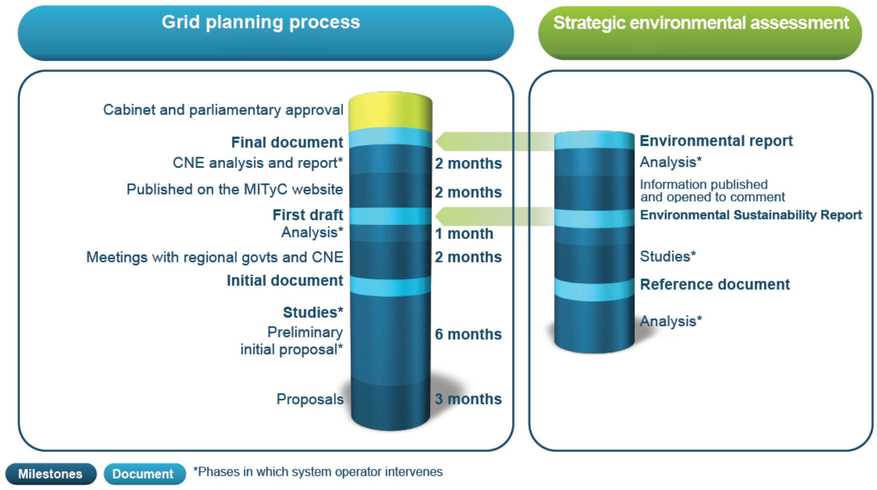

Figure 4.2 - REE Transmission Planning Process - source: [78]

This procedure is very similar to the Portuguese case except for the fact that here the government takes an active role in the planning activity.

4.3 - EirGrid

EirGrid is the Irish TSO. Like the other entities presented, it is committed not only to the operation but also the planning of the TN.

Balancing reliability, sustainability and costs is the pointed out baseline for the planning activity: all that through an economical way.

Grid25 is the long-term development strategy for the grid; it is described as being “a major initiative to put in place safe, secure and affordable electricity supply throughout Ireland, supporting economic growth and providing a roadmap to a bright future for renewable and sustainable energy”.

It presents the development strategy over the period to 2025. Similarly to the Portuguese case, the main objectives in which the planning activity is drawn upon are the growing integration of renewable energy sources, increasing connectivity capacity to European grid and ensuring network reliability and security of supply.

A “balanced forward-thinking approach” is adopted so that the environmental impacts could be minimized. Also, along with the whole process, there is an assessment of the costs that each proposed solution bears, in order to achieve the most efficient planning.

Figure 4.3 - Grid25 process – source: EirGrid [79]

EirGrid carries on studies on the network future demands and, by coping with standards from government (Communications, Energy and Natural Resources Ministry) and the Commission for Energy Regulation, a process for developing grid solutions is developed (proposed solutions).

This process takes into account the impact of the overhead lines construction on the environment and local communities. “EirGrid engages with national, regional and local stakeholders around the country through a synergy with Chambers Ireland”; this is a “social partnership organization that represents the interests of member companies to promote competitiveness and development”.

After these main stages, the planned network investments are presented and consequently implemented.

4.4 - Conclusions

Three examples were shown which depicted the TEP process carried out by foreign entities. It should be highlighted that different types of entities responsible for carrying out the TN planning activity or that take part in it were presented.

Even though the core of the planning processes couldn’t be reached by this type of research, some conclusions/comparisons could be drawn with respect to the case study: Portuguese TEP.

REE and EirGrid take, importantly, into account the environmental impacts of the TN expansion, as it is a part of their energy and sustainability policies, like REN.

PJM and EirGrid procedures reinforce the fact that stakeholder input is a key issue to the adequate planning process either by raising and identifying possible improvements or by taking part in the analysis/assessment of the planning criteria.

With respect to the costs, its consideration as a priority factor differentiates somehow these studied cases from the Portuguese case. No information about the way the cost consideration is implemented in the planning processes was made available; only that it’s a differentiating factor for the selection of expansion solutions/alternatives: it's the pursuit of the choice of the solutions that best cope with the planning criteria, in the least-cost way.

Regarding the planning criteria there are many correspondences between the presented examples and this work case study. As was already stated, the Portuguese TEP process can be, in a generalized way, considered as thriving because it encompasses a valid set of planning criteria as well as an adequate methodology for developing this process.

In the following chapter a decision-aid methodology for coping with the multi-criteria nature of the TEP is presented.

Chapter 5

Proposed Approach

After an analysis over the Portuguese TN development plan – PDIRT - some comments were drawn relating the current strategic planning approach.

Taking into account the vast number of issues that can be identified around the TEP problem, a multi-criteria decision-making approach is, here, proposed.

5.1 - Decision Analysis

Decision Analysis has progressively become a core issue for organizations that intend to develop their processes towards an improvement in efficiency.

The study and development of this subject-matter helps decision-makers to take the best decisions that, inevitably, conduct to the best outcomes. The implementation of decision-making techniques allows facing problems with better understanding, which may lead to the best decisions.

This subject is often conditioned by subjective judgments: problems aren't always straightly objective; therefore some input from the decision-maker is, many times, required. Thus, when prompted, he must be able to take the best judgments, identifying the decisions that better improve the needed outcomes.[80]

The decision making process incorporates some issues that must be carefully addressed, such as the identification of alternatives and their viability and the definition of evaluation criteria.

There are several types of decision problems: selection, ordination and partitioning problems. The problem underlying this work can be formulated as a selection problem, addressing the selection of an alternative specifically the best for the TN expansion/development.

Each alternative is described as an "option, hypothesis, possible solution or potential action, being described by its attributes which define it completely in the decision process".[81] The attributes are, simply, the "levels/values" assigned individually to each alternative by evaluation criterion. That is achieved through the selection of an appropriate scale of values (and sometimes the units) that, without ambiguity, can characterize the impact that each criterion establishes, individually, onto each alternative.

Depending on the chosen criteria, numerical or qualitative scales may be used. Then, depending on the objective of the decision problem, alternatives may be picked through the assessment of all its attribute values.

The evaluation criteria must identify the determining aspects upon which the decision process takes place. It's by evaluating such criteria that the decision maker may set his preferences. He is the responsible for conducting the process and therefore the achievement of a final solution cannot be done without his own input into it: as already expressed, due to the inevitable subjectivity of his judgments, the process should be as clear as possible so that the subjectivity could be reduced.

When there are several criteria at stake, the whole decision process becomes increasingly complicated. Due to the conflict of criteria, that is usual in real problems, it becomes difficult to assess the best alternative, not being possible to choose one that is better than that of the competitors in all criteria.

In these cases, the simple attribute settlement isn't enough to establish a way of choosing the best alternative. This is where the decision maker is prompted for adding input to the decision process; that input is his overall establishment of preference by assessing the evaluation criteria. In this case it may be noted that "in multi-criteria problems there isn't an optimal solution that could be chosen without arousing controversy but a preferred solution that can differ for different decision makers".[81]

A good way to deal with this issue is the establishment of substitution rates between alternatives: the decision-maker is prompted to set how should mark the exchange of alternatives; in other words, trade-offs can be established so as to represent the decision maker preferences.

By establishing preferences between alternatives, the decision maker creates a relation between the correspondent attributes, with subjective significance – indifference establishment.

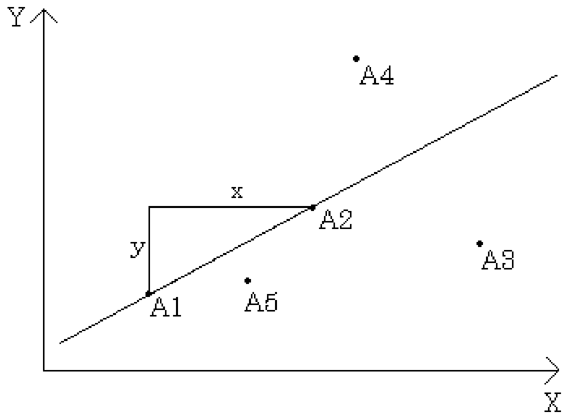

Figure 5.1 - Trade-off establishment between alternatives.

The process is simple and the above picture allows a better understanding, depicting a two-criterion case. Taking it as example, there are five alternatives that are being assessed by criterion X and criterion Y (maximization of criterion Y). If the decision maker considers alternatives A1 and A2 to be indifferent - A1~A2 - (having the same value) then a relation between the two criteria (x/y, in their respective units), that satisfies his preference, is found. This way an assessment of all alternatives towards choosing the best is now possible.

The meaning of that relation could be described as how much the decrease in one criterion (x) compensates an increase in the other (y).

The line that crosses the two indifferent alternatives is called line (curve) of indifference. Depending on the type of problem, maximization or minimization, its inclination determines a family of curves that when drawn allow the geometric determination of the best alternatives, depending on the desired graph zone in consideration (according to being a maximization or minimization problem). Another important aspect is that all points placed under it have the same global value.

Alternatives that are placed after the curve, in the opposite way of desire, when it stands over one alternative, are considered dominated by it as there is always one alternative that is better in at least one criterion, never being worse in the others.

By considering different replacement rates between criteria, the decision maker establishes different ratings of the importance for them. If one criterion is fixed (for example, the one considered as most important) when compared with the remaining ones, then it’s possible to conjugate the preferences of all criteria, relating to it, as an overall value.

For a convenient operationalization of this methodology, Additive Value Functions can be implemented and extend the process to a wide number of criteria. It is a possible approach to address this multi-attribute problem.

This way, the construction of a model for the representation of preferences can be effectively achieved through an Additive Value Function. Thus, the model to be adopted may be described analytically:

$$V(x_1, \dots, x_m) = k_1 \times v(x_1) + \dots + k_m \times v(x_m) = \sum_{i=1}^{m} k_i \times v(x_i) \qquad (5.1)$$

where V(x) is the function that returns the value of each alternative; "k_i" are the weights, being that each one is specific to each criterion (x_i); $v(x_i)$ is the individual value function: in this case, it's the attribute that the assessed alternative has relating to each criterion (x_i).

All the weights are positive and their sum is 1, which implies a normalization process. They are set by addressing indifference judgments to the decision-maker.

The model presented will have into consideration that the individual value functions are linear and the weights constant (constant trade-offs that imply linear indifference curves).

The way this model may be applied to the problem in hands is presented below.

5.2 - Proposed Problem Formulation

Departing from the decision analysis presented before, we must affirm that in order to formulate the problem correctly, the alternatives must be completely defined and assumed as feasible.

An aggregation model is proposed towards the resolution of the TEP problem, to aid in the choice of the best expansion alternative.

In an attempt to disambiguate and clarify the PDIRT's TEP process, the proposed approach will retain the baseline criteria used by REN and perform some implementations at a decision making level of the strategic process.

As it is clearly identified in PDRIT, the EE is a core issue of the planning process. In that document the assessment of the alternatives appears divided in two tables: on one the results of the EE are presented and on the other, without any link, there is the assessment under two criteria: SRG acceptance and flexibility.

What is here proposed is an aggregation model that can embody those "two stages" of assessment in a single one. More concretely, the construction of a bi-level DSS is objectified, to deal with the choice of alternatives.

The intent is to cluster the main planning criteria on a single level for the consequent assessment of alternatives; this would be called the first level and the proposed criteria are:

- Flexibility – remains the same criterion as was designed by REN: ability of each alternative to receive, without the need for reinforcements, unanticipated changes in the volume and geographic location;

- SRG acceptance capacity – this also remains the same criterion and relates to the capacity of SRG acceptance beyond the pre-established goals.
- EE – aggregation of the assessment of the EE evaluation criteria (transits from level 2). It represents the positive impact that outcomes from the EE.
- Cost – this should represent the cost that the adoption of each alternative bears (in M€). The inclusion of the Cost factor in this decision making process is indeed important because it is unavoidably an important differentiating factor.

On a second level, the EE assessment of each alternative would take place by the REN's stipulated CDF evaluation criteria; then, those attributes would be aggregated in a single score/value that will transit to level one, as the correspondent result of the EE assessment for each alternative. A schematic representation is presented below.

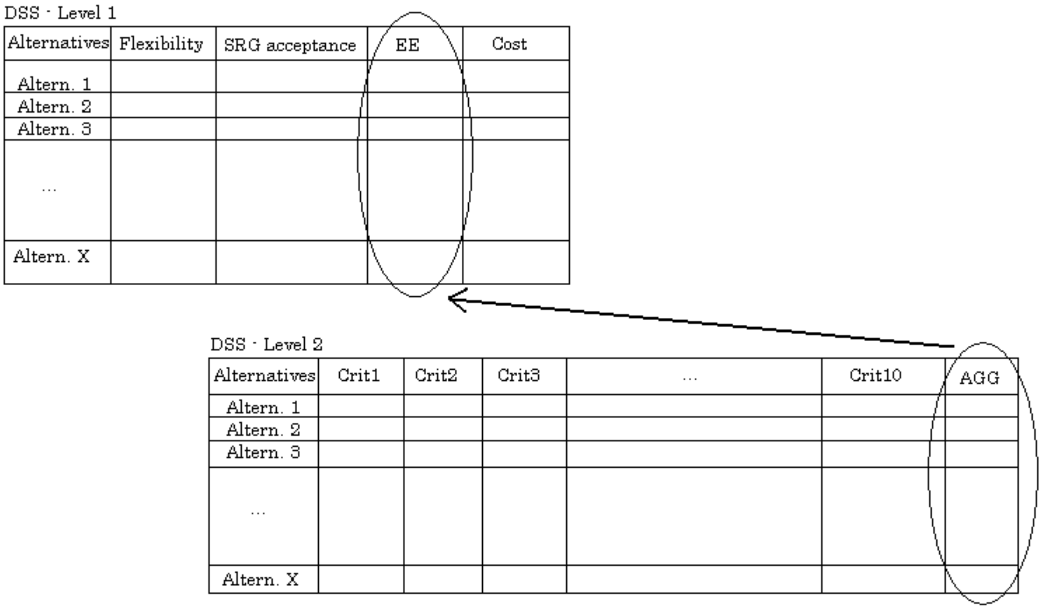

Figure 5.2 - Schematic representation of the proposed aggregation model.

Expressed in the form of tables, the approach here proposed differentiates two decision support levels.

The idea is that after setting the attributes for all criteria in Level2, an additive value function aggregates those attributes in a single score for each alternative being, then, inserted in the correspondent place on the Level1 EE column. Then, by fixing the Cost criterion, on the first level, an equivalent cost for each alternative will be calculated so that the best can, then, be chosen.

The scale values proposed for the criteria and the way the decision maker establishes his preferences are presented afterwards.

With respect to the first level of the DSS, as the EE attributes are set by the aggregation values descendant from the second level the manual settlement of the remaining is needed, so as for all in level two. As being a quantitative model of preferences, it can be highlighted that all attributes used are deterministic (numerical).

For convenience, all attributes should be designed in a way that all are intended to be maximized or minimized. In this case that will happen on the second level but on the first level the implementation will be a little different.

5.2.1 -DSS level 2

The DSS second level incorporates the EE evaluation criteria assessment. For a question of parallelism with the actual TN planning exercise the criteria used are those defined by REN (CDF evaluation criteria), which are ten.

In the implemented interface they are identified as: SP1, SP2, SP3, FAUNA1, FAUNA2, FAUNA3, FAUNA4, FAUNA5, ENERGY1 and ENERGY2. These criteria description can be found in Annex B. Even though the inclusion of the Energy evaluation criteria in this level could be questionable, since (as stated in chapter three) they are, somehow, already represented in level one, it was chosen to keep the criteria the way REN presented in PDIRT (notwithstanding it being able be reviewed at any time).

As an Additive Value Function will be implemented, it implies that the attributes are numerical. Therefore, the following scale was developed:

Table 5.1 — Scale of values proposed for the assessment of the alternatives in the DSS second level.

Value	Level
0	Very Unfavorable
1	Unfavorable
2	Indifferent
3	Favorable
4	Advantageous

As it is well evidenced in the table above, at this level the EE criteria are evaluated in a positive way: despite being negative the impact that the TN expansion causes on the Environment, the criteria are assessed in terms of positive environmental impact, where by setting 4 in any attribute represents assigning the most “environmental friendly” level. Therefore, all criteria here are meant to be maximized.

After filling in all attributes, the decision maker must be prompted for establishing his preferences: he must firstly choose which criterion he considers as being the most important; then, that criterion is fixed and he will, individually, for each of the remaining criteria, set how much should the most important criterion rise (from zero) to compensate a supposed reduction of 4 to 0 (max to min) in each criterion (being the choice of intermediate values possible: for example, if unsure between setting level 1 or 2 then he may set 1,5). This way, he will be establishing indifference levels that will be incorporated in the Additive Value Function weights (k_i).

Then, those weights are normalized (by dividing by the sum) and will multiply by the correspondent attributes, so that an aggregation value is achieved. That value will represent (in the scale used: 0-4), the overall positive environmental impact of each alternative, transiting afterwards to the correspondent column on level one.

$$k_i = (X \cdot k_a) / 4 \qquad (5.2)$$

In 5.2 is described the incorporation of the decision maker preferences in the aggregation function, where k_i is the weight resultant from each individual criterion; ka represents the most important criterion (which will be fixed with the value of 1) and X is the compensation in the (selected) most important criterion regarding an individual change from max to min (4 to 0) in the each criterion. The factor 4 represents that same max to min variation. Then, the weights are normalized (divided by their sum) and will enter 5.1, multiplying each correspondent individual value function ($k_i \cdot v(x_i)$).

This procedure represents the establishment of value compensations two by two criteria. As one is fixed (the most important: k_a=1) it's, then, possible to determine the value of each correspondent weight.

5.2.2- DSS level 1

This level is intended to be the main level, where the crucial choice of the alternatives takes place. Then again, the attributes have to be set (except for EE) and the decision maker must transmit his input to the process.

Relating the attributes settlement, some considerations must be made. In the previous level the scale used ranges from 0 to 4 (being 4 the highest level). The aggregation values, that outcome from the EE assessment in the lower level, may have many decimal places as they result from the application of the implemented Additive Value Function; as they transit to level one and the use of an integer scale is desirable, at this level, the proposed scale for all criteria but Cost is:

Table 5.2 — Scale of values proposed for the evaluation of the SRG acceptance, EE and Flexibility criteria in the DSS first level.

Value	Level
0	Very Poor
10	Poor
20	Fair
30	High
40	Very High

This presuppose that when those values transit from level two to level one, they are multiplied by a factor (10) to enter the new scale. This is the equivalent of considering the information value of only one decimal place of the (level2) primary value, which increases the precision of the process (instead of truncating or rounding the number's decimal part). The fact that an integer scale is preferred relates to a matter of convenience regarding a possible simplification of the decision making process, making it more intuitive.

In this case it is, then, considered that the use of intermediate levels for the assessment of SRG acceptance and flexibility isn't necessary, since their potential value variation can be well addressed by the five levels suggested; another aspect to state is that, in terms of importance, those five levels are equally spaced.

On the other hand, the resulting values for EE criterion may take intermediate levels in the proposed scale. This was specifically considered since there is a more exhaustive process behind the EE assessment: it is the outcome of a weighted evaluation of ten criteria by the decision maker subjective preferences. Therefore, more detail should be incorporated in the alternatives' EE attributes. As may be seen later, this also brings some advantages in terms of implementation.

This way, uniformity (accordance) between the EE, SRG acceptance and Flexibility related attributes can be reached. Regarding these criteria values it must be said that, like EE criteria already described, they are assessed positively: the bigger the values set, the best the correspondent criteria acceptance.

With respect to the Cost criterion, its natural values are used: M€. Unlike the other criteria, Cost is determined as having a negative impact. So, this criterion is meant to be minimized, for the achievement of the best solution.

Now that the first level attributes can be appropriately set by the decision maker, the question of the selection of the best alternative arises. Then again, he is prompted for his subjective input. In this case, the criterion Cost will be fixed, since it is considered (naturally) the best differentiating criterion, and three trade-offs will be established: α_f(M€/Flexibility level), α_s(M€/SRG acceptance level) and α_e(M€/EE level). The decision maker must select, for each criterion, how much would lowering one level cost; for example how much in M€ would the transition from Very High to High cost. The establishment of these trade-offs, that are constant, will allow the determination of an equivalent cost for each alternative:

$$EC_i = C_i - \alpha_f \times F_i - \alpha_s \times S_i - \alpha_e * E_i \qquad (5.3)$$

where EC_i represents the equivalent cost of alternative i that is achieved by multiplying each trade-off for the correspondent criterion value (F_i, S_i and E_i are the values of the criteria Flexibility, SRG acceptance and EE, respectively); C_i is the cost of alternative i.

As expressed before, Cost, by having a negative impact on the solution desirability, appears in the function with a different sign from the other criteria.

Finally, the best alternative, or the alternative considered as desirable is the one characterized by the lowest equivalent cost.

This is a simple and useful methodology for coping with the multi-criteria problem in hands. For a better understanding, the way it was embodied in the developed interface is presented next.

5.3 - DSS developed interface

The proposed approach was presented as an aggregation model. Then it was proceeded to its implementation.

With the objective of creating an interface able of incorporating the suggested decision-aid model, an application was developed in the open source LAZARUS software. It is and IDE with GNU-GPL license (General Public License) for creation of applications; it uses Free Pascal programming language (being compatible with Delphi).

By being a visual, event-driven, programming software that allows the creation of forms and database management it emerged as a good option to implement the desired DSS.

Even though the development of projects in this IDE is often related to the use of SQL – Structured Query Language – which requires the additional use of elements external to LAZARUS for running applications, a solution that goes through the use of the TDBF module was adopted. That is a “freeware native data access component which allows creating very compact database programs”[82] (which is the case) and is compiled directly into the developed project executable file. Therefore, the DSS can be clustered into a single file.

An example of a decision making problem in the developed application is presented to illustrate its operation.

Starting from the lower level (level2), the user should start by filling in the attributes correspondent to each EE criterion (in the following example, TO represents the Spatial

Planning criteria). The correspondent scale is displayed on the right side as may be seen in the figure below.

Then, he must proceed to the parameterization of the Aggregation Function, by clicking on the button "Param. Aggregation". This will open another window where the user can establish his preferences in terms of criteria. The Aggregation function is no less than the Additive Value Function applied in this level.

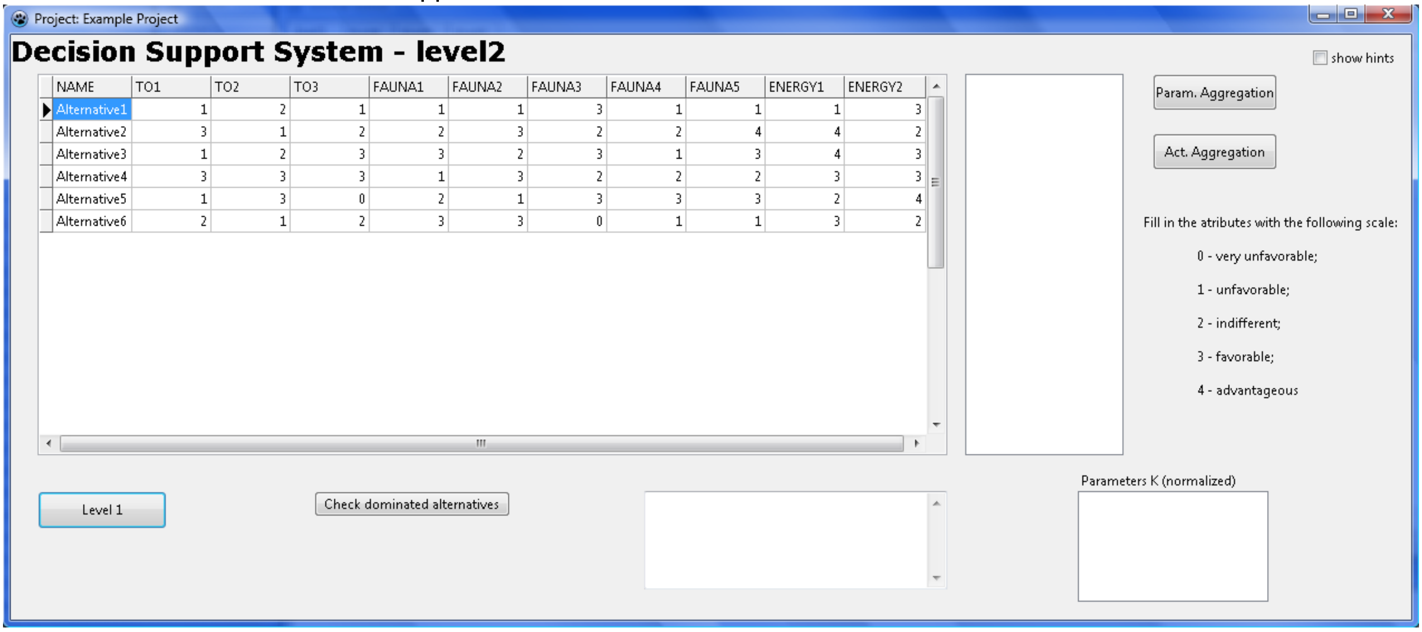

Figure 5.3 - DSS level 2.

The parameterization of the Aggregation Function will be the definition of the weights that characterize the Additive Value Function by the establishment of indifference. For this, the graphic interface below was developed. The information needed by the user for taking action is conveniently displayed.

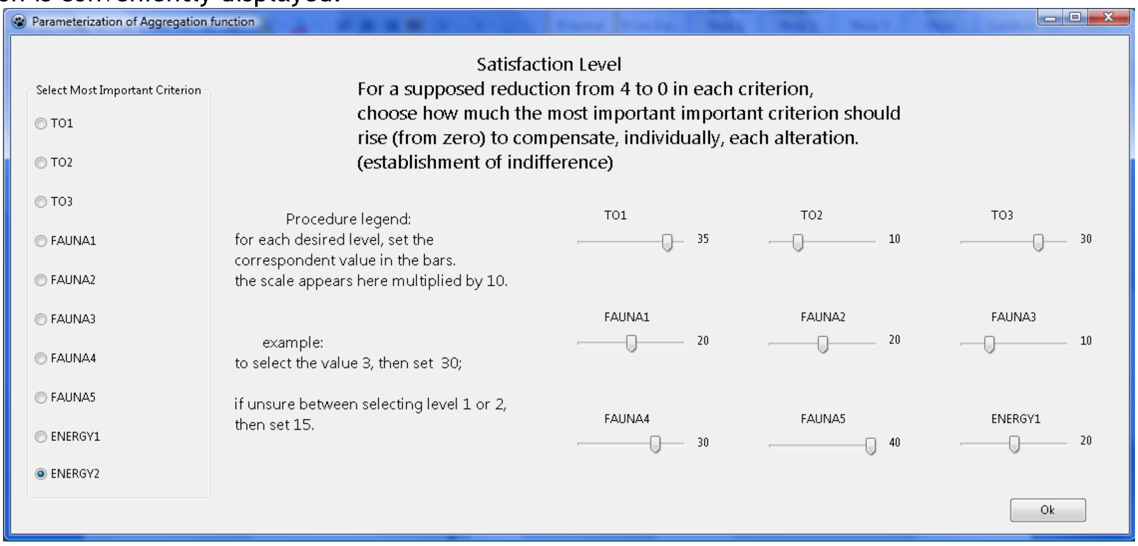

Figure 5.4 - Interface for parameterization of the aggregation function.

Firstly, the user must choose which criterion, from the list of ten (mutually exclusive), he considers to be the most important. Then, by sliding each bar individually, he will choose how much the most important criterion should rise to (from zero) to compensate a reduction from the maximum to the minimum (4 to 0) in each criterion. There is a procedure legend to help set the values.

The selection of the most important criterion is exclusively independent: only one may be chosen at a time and the bars adapt automatically to exclude that criterion from the individual establishment of indifference bars.

Pressing the “ok” button, the previous window will appear.

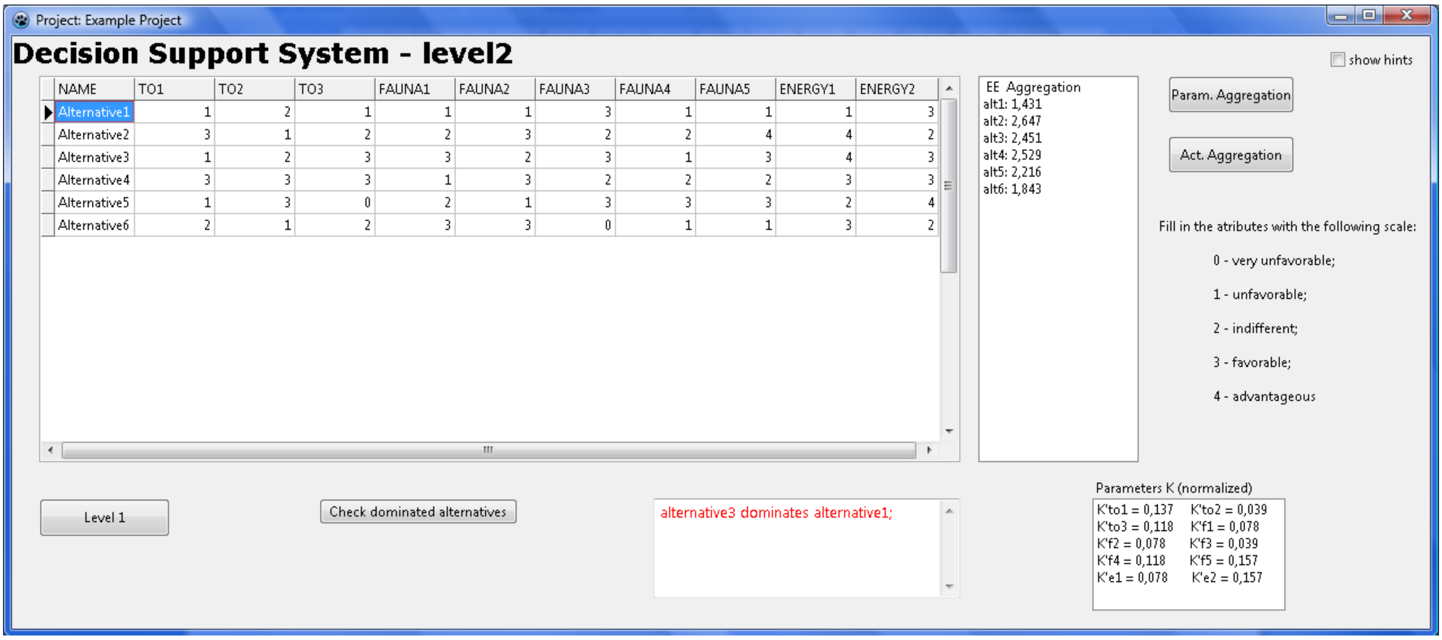

Figure 5.5 - Aspect of level 2 after calculating EE aggregation values.

The “k” parameters that incorporate the Aggregation Function are now displayed (normalized) in a box, near the lower right end (just to give the user an idea of the weights currently in use). Now, that the parameterization is done, pressing “Act. Aggregation” will display the outcome value of the function for each alternative in a box right next to the table. Every time the user proceed to any change in the attributes it is simply enough to press that button again, in order to update the EE aggregation values. Whenever that is done those values transit automatically to the correspondent column on level one.

There is a procedure implemented to verify if there are dominated alternatives and, in that case, to display a message in red in a text box at the bottom of the window. That verification occurs each time the “Check dominated alternatives” button is pressed.

The buttons placed near the lower left ends of both DSS levels allow instant switching between them.

The DSS first level window is similar to the previous one. It displays a table where the alternatives will be evaluated by criteria. In this case, the EE column is automatically filled in with the values descendant from the EE aggregation in the lower level, occurring automatic change of scale. From an implementation perspective, there is a limitation that supports that fact: the modules used are only able to display numerical data of integer type.

Nonetheless, as already stated, the option for the use of a new scale in the first level was also justified as an attempt of standardization between criteria in a more intuitive way, neglecting the use of numbers with decimal cases.

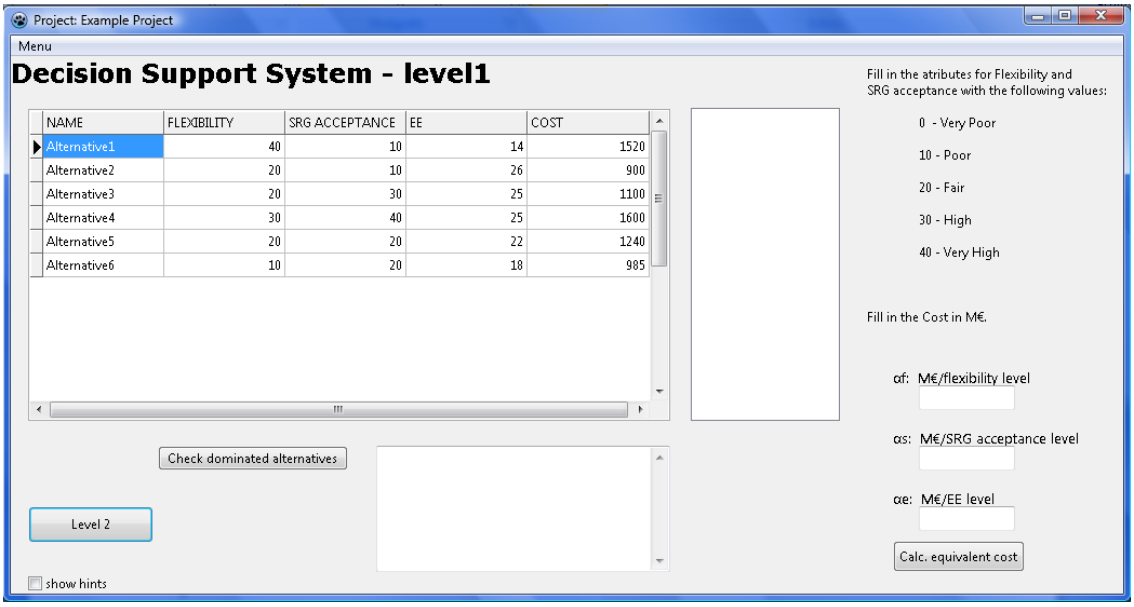

Figure 5.6 - DSS level 1.

The instructions for filling in the attributes are displayed and thereafter the user must determine three trade-offs (as was described in the previous section): αf, αs and αe. As the use of constant trade-offs was intended in order to make the judgments of value, the user must insert the desired values in the corresponding boxes. Then, by pressing the “Calc. equivalent cost” the equivalent costs, computed after the user preferences, are displayed on the box next to the table.

Now it’s possible to choose the desirable alternative by selecting the one that presents the lowest equivalent cost. In the presented example, the alternative to be chosen would be number two, with the (lowest) equivalent cost of 442M€.

This is the window where the (main) menu is located, with the options: “New Project”, “Open Project” and “Close Project”. Also, there is a check box located in each DSS level that allows enabling or disabling hints. Those hints are text boxes that appear whenever the mouse pointer goes over an item, providing useful item-related information.

Another aspect worth stating is the fact that there is also the possibility to check for dominated alternatives, like in level two. It is worth saying that this is a basic procedure that only takes dominancy of alternatives regarding the attributes present in the table into account; the trade-offs set by the user don't interfere here nor with the equivalent costs.

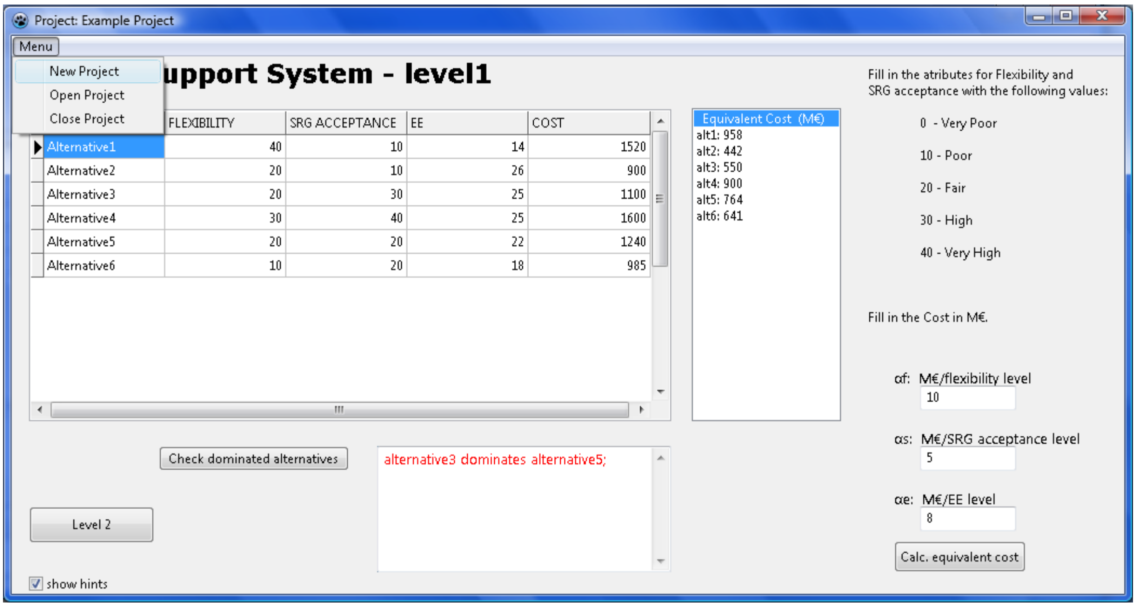

Figure 5.7 - Aspect of level 1 after calculating the Equivalent Costs.

This presentation of the interface is intended to provide an example of its use. An illustrative example was used in the case presented for best describing the application operation.

5.4 - Conclusions

A possible approach for coping with the TEP was presented.

It is based on the construction of additive value functions and the establishment of indifferences/trade-offs by the decision maker so that his preferences can be incorporated in the strategic planning process, culminating in the selection of an alternative that can be classified as the best/preferable by the evaluation of an equivalent cost (indicator). Therefore, cost is assumed as a criterion and is used for differentiating the alternatives choice.

In this multi-criteria approach the set of criteria considered was that presented by REN in the PDIRT elaboration; that was for better exemplifying how the proposed methodology would fit in this planning exercise. However, the set of criteria could be revised at any time.

A DSS was developed in the LAZARUS software platform and an intuitive example of its interface use was presented. The application developed claims to be a simple and effective interface for the assessment of several alternatives towards the selection of the best for the user (according to his subjective judgments). It also intends to be an improved way for structuring the REN's EE process by ranking and ordering the planning criteria.

The selection of the scales used for assessing the criteria tried to be the most intuitive as possible. Nevertheless, there are two types of scales at use (one in the first level and another in the second – besides cost, that keeps its natural values). That may be become less clear for the decision-maker, but it's both due to a limitation at an implementation of the interface-application and simply by the convenience of avoiding the use of values with decimal places.

Chapter 6

Conclusions

It was presented the study/work carried out in the subject: selection of strategies of planning for the TN.

It started from a framing attempt on the TEP activity where its main subjects were addressed in a descriptive way with an acquaintance purpose. It became clear that it isn't an easy problem to solve, mostly because of its high complexity level. Also, the Portuguese TN, which is this work case-study, was briefly characterized.

Regarding TEP, a differentiation was made: strategic as well as mathematic network optimization models are two possible approaches to the problem. The first is the one on which this work was based.

Nevertheless, chapter two addressed mathematic network optimization approaches with the intent of broadening the extent of the insight in the TEP subject-matter. An illustrator compilation of several types of mathematic network optimization methods was presented as well as a brief presentation of some of the most mainstream.

The PDIRT document, that states the investments for the Portuguese TN expansion and the development headlines, was presented and analyzed.

The first aspect that comes out is that the TEP procedure incorporates a comprehensive EE assessment, which may be considered successful as it considers a wide range of valid subjects, incorporated in the CDF. An attempt of finding/suggesting new evaluation criteria was made, but proved unsuccessful since either little information is made available by the entities that are responsible for the TN planning activity or the Portuguese TSO has already incorporated the criteria used by its counterparts.

With respect to the choice of expansion alternatives (which is the departing point for the EE), REN establishes ensuring the best operation of the TN as a fundamental, putting the effectiveness of operation and sustainable development policies in first place.

From the survey made on the TEP procedures carried out by foreign entities (exemplified in chapter four), it may be concluded that the methodology used by REN for the TN planning is at the same level (of demand) as those developed by, what can be considered as, its high efficient counterparts. It follows the generalized trend for the planning criteria: the increasingly consideration of inclusion of renewable sources, SRG acceptance levels, reduction of greenhouse gas emissions, enhancement of interconnection capacities, etc.

Despite that, no information relating the costs consideration for the choice of expansion alternatives is transmitted. From this, it can be inferred that this factor doesn't condition the selection of alternatives and REN doesn't take it into account at this stage or it was omitted for not being considered a decisive factor in the strategic level of the TN development. Nevertheless, the PDIRT document possesses the necessary elements for the establishment of a multi-criteria decision-aid for coping with the TN planning problem.

As there isn't any specific global indicator able of differentiating (ordering by value) the desired TN expansion alternative an approach of the TEP problem that integrates the criteria currently used by REN was presented.

With respect to the developed approach, it was based in the application of judgments of value by the decision-maker; additive value functions were used to formalize it.

An aggregation of the process of evaluation of alternatives was implemented in a similar way to the case-study: it was used the set of criteria considered by REN, differentiating the EE assessment to a lower level. Then, an implemented procedure allows the aggregation of criteria on a single level, so that, through the calculation of an equivalent cost, the best alternative could be chosen.

The proposed formulation is easy to implement, intuitive to use and is capable of reaching feasible solutions, aiding the decision maker through the strategic planning process.

Further development of this proposed approach could go through the use of more complex value functions (non-linear) able to incorporate varying trade-offs established by the user: the fact that beyond certain levels the subjective judgment of the decision-maker can change (corresponding non-linear indifference curves) may conduct to enhancements in the process for the selection of the best alternative.

Either other criteria or a different type of aggregation could be used, which through the adaption of this method can lead to the inclusion of more stakeholder input and a consequent more effective DSS.

Another aspect worth of stating for future work is the possible introduction of mechanisms to prevent the decision-maker from taking contradictory decisions. As a final remark, the decision-aid model developed requires validation and should hereafter be tested by decision-makers that take part in the TN planning/development.

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Annex A

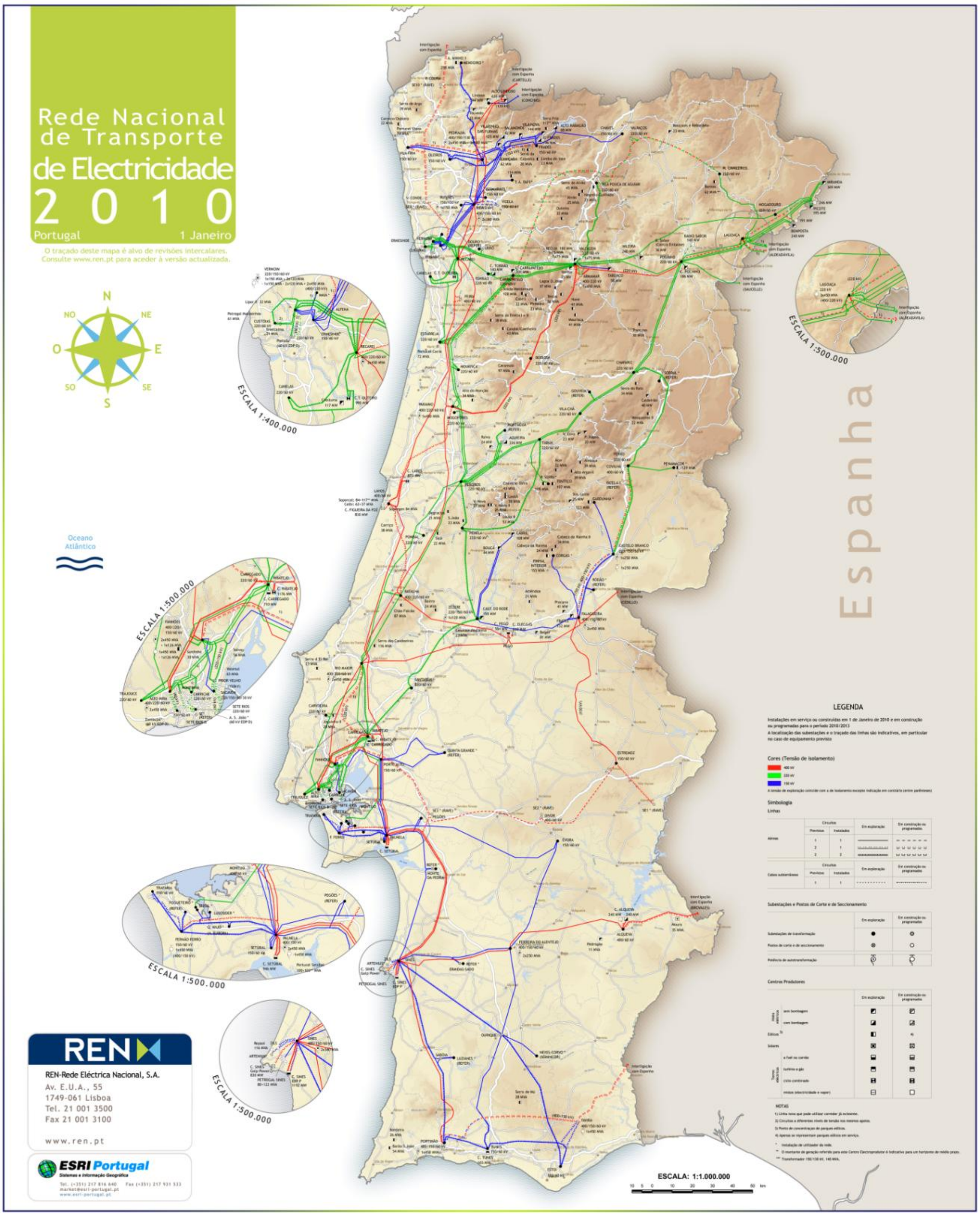

Figure A.1 - Map of the Portuguese Transmission Network.

Annex B

CDF description

CDF Fauna

Objective: assess the impact of new investments in the network expansion in classified areas and in flying vertebrates' populations.

Criterion 1) Intersection of classified areas: [FAUNA1]

Classified areas contain relevant natural and heritage elements. Their crossing may affect those elements, which may lead to animal population fragmentation and landscaping degradation. In some cases, there may be management or ordinance plans that allow classifying and ranking the crossed territory.

Indicator: Extension of line corridors that, for each strategy, cross each classified area. In case of any ranking existence, the territory crossed may be classified in terms of value.

Criterion 2) Crossing of critical zones of species (except birds and bats): [FAUNA2]

As a protected species, the wolf packs are drawn a special attention. The corridors crossing that species' protected areas may cause an undesirable impact to the populations.

Indicator: Extension of line corridors that cross major areas regarding known packs of wolves' conservation.

Criterion 3) Crossing of birds critical zones (unfavorable conservation status): [FAUNA3]

Some bird species may be likely to hit the power lines; some of them bear the status of unfavorable conservation. The planning must take into account the populations' location and migration movements, in order to minimize interference.

Indicator: Extension of the line crossings through susceptible areas (habitat and know migration corridors).

Criterion 4) Proximity to bat shelters of national importance: [FAUNA4]

Although the effect of the power lines on the bat population isn't well known, it has been clear that it is important to safeguard the areas where there is important concentration of this species.

Indicator: Distance to known national bat shelters.

Criterion 5) Cumulative impact minimization: [FAUNA5]

The placement of multi-structures for the energy transmission imposes undesirable factors to many animal species: the fragmentation of the territory and a barrier effect. Here urges the need for the definition of preferential power line corridors and the minimization of the barrier effect

Indicator: extension of fragmented territory; critical distance between transmission system infrastructures.

This CDF assessment is supported by the resolution of the potentially affected populations' dimension.

The information needed is gathered in sources such as studies developed by universities and NGO's and the "New Atlas of breeding Birds in Portugal" and are, then, inserted in a SIG allowing posterior geographic analysis.

CDF Spatial Planning

Objective: analysis of the actual situation and identifiable trends in the PDRIT horizon in matter of conditioned areas, landscape, heritage and population issues in order to assess, comparatively, the alternative scenarios for the network configuration.

The studies pursued in this CDF scope shall allow the identification, localization, analysis and evaluation in a macro-scale (1:250.000) and in a dynamic perspective (trough the PDIRT horizon) of the following parameters:

- Human presence – infrastructures, population density, relevant activities;
- Sensitive areas;
- Constraints capable of interfering with the transmission network such as heritage, environmental, landscaping and cultural.

Criterion 1) Interference with sensitive areas (environmental/heritage protection): [SP1]

Minimize the interference with sensitive areas, heritage elements and preservation of landscape values.

Indicator: number of occurrences of crossed zones (or in the vicinity), by typology.

Criterion 2) Interference with areas of infrastructures and strong human presence: [SP2]

Minimize the interference with big infrastructures, areas legally conditioned and soil use of areas with national/regional relevant activities (tourism, leisure, cult).

Indicator: number of occurrences of crossed zones (or in the vicinity), by typology.

Minimize the interference with areas of strong human presence.

Indicator: relevant crossing occurrences (or in the vicinity); assessment of areas by classes – dimension classes, growth taxes.

Criterion 3) territorial TSO potentiating (REN): [SP3]

Potentiating of production acceptance and synergistic effects with the current network.

Indicator: number of occurrences of zones with other existing lines; number of occurrences of production centers (existing or predictable) by dimension and typology.

The information gathering will be grounded on a compilation of the existent publications and analyzed taking into account the trends depicted in the underlying Strategy Reference Framework.

Then, the information will be cartographically transposed for a macro-scale delimitation of the areas capable of potentiating the expansion of the transmission network.

CDF Energy

Objective: The two main objectives are the loss minimization and consequent system stability improvement – efficiency – and the production acceptance, contributing for the enlargement of the connection of more generation and the use of renewable sources of energy – decentralization of energy production.

Criterion 1) Production acceptance (SRG): [ENERGY1]

It is necessary for the production to have a means of acceptance; that is a requirement of the transmission system. It is important to guarantee the capacity for the acceptance of renewable energy production, to strategically contribute for the reduction of gas emissions and pollutants, due to the reduction of the fossil fuels use (according to Quioto Protocol headlines).

Indicator: index of use of equipments in key areas of renewable energy generation; proportion between the evolution of the investments in renewable energy generation and the progress in its consumption; grid acceptance capacities.

Criterion 2) Energy efficiency (loss minimization): [ENERGY2]

The security and quality of the network can be achieved through investments directed to its structural improvement. Those benefits bring direct advantages over the energy transmission efficiency – loss reduction.

Indicator: Loss value forecast.

The analysis of the information available by REN is of great importance; both statistical information and various reports allow the structuring of the CDF's. Information provided by other sources (external entities) is also of great importance in order to help understanding the network power loss issue.
The forecasting and comparison of several scenarios of posterior years permits consolidating the notion of the transmission network evolution.